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AN EXPERIMENTAL COMPARISON OF A PIN STACK TO A CONVENTIONAL STACK IN A THERMOACOUSTIC PRIME MOVER

By

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AN EXPERIMENTAL COMPARISON OF A PIN STACK TO A CONVENTIONAL STACK IN A THERMOACOUSTIC PRIME MOVER

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ABSTRACT

This thesis is an experimental comparison of a pin stack to a conventional rolled stack in a thermoacoustic prime mover. A thermoacoustic prime mover is a type of natural heat engine which converts a temperature gradient across a stack into acoustic energy. A pin stack uses wires which are arranged in a hexagonal array instead of the parallel or rolled plates of a conventional stack. The pin stack was constructed by threading 75 micron constantan wire between the hot and cold heat exchangers 2312 times. Computer modeling with the program DeltaE predicts that a pin stack will significantly improve the efficiency of the prime mover. In the experiment the temperature gradient across the stack was supplied by submerging the cold end in liquid nitrogen while holding the hot end at ambient temperature. The experiment was conducted for both the pin stack and a conventional rolled stack. The pin stack produced 20 % higher acoustic pressures than the rolled stack and the efficiency was up to 31% better. The pin stack went into onset at a 41% lower mean pressure then the rolled stack.

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LIST OF SYMBOLS

c	sound speed
c_p	isobaric heat capacity
f	frequency
K	thermal conductivity
L	resonator length
P	pressure
Q	quality factor of resonator
Q'	heater power
r_i	pin radius
T	temperature
W'	acoustic power
y_o	array half-spacing
Δx	stack length
β	thermal expansion coefficient
δ_κ	thermal penetration depth
δ_υ	viscous penetration depth
γ	ratio of specific heats
λ	wavelength
μ	dynamic viscosity
Π	perimeter of stack cross section
ρ	density
ω	angular frequency

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I. INTRODUCTION

A thermoacoustic prime mover is a natural heat engine which converts heat flow from a high temperature source to a low temperature sink into acoustic energy. The stack supports a smooth temperature profile between hot heat exchanger and the cold heat exchanger. The conventional or parallel plate stack used in this experiment uses a spiral wound sheet of polyester as the stack material. A pin stack uses pins, or wires, aligned with the acoustic axis of the prime mover as the stack material (Swift and Keolian, 1994).

In the 1994 article Swift and Keolian predict that a pin stack will be significantly more efficient than a parallel plate stack. In a pin stack the ratio of the volume of gas that contributes to the acoustic work to the volume in which dissipation losses occur, is larger than that for a parallel plate stack.

The prime mover used in this experiment was developed by Castro(1993) for his thesis which investigated heat exchanger performance. The parallel plate or rolled stack described by Castro is the stack which was used in this experiment. This performance of this rolled stack will be compared to the performance of the pin stack.

The pin stack was designed by Nessler(1994) based on results of a comparison conducted in his thesis with the computer model DeltaE (Ward, 1993). The design consists of 75 micron wire wound 2312 times between the hot and cold heat exchangers. The wire is arranged in a hexagonal lattice with a spacing of 750 microns.

In this thesis, the pin stack was constructed and an experiment was conducted for both the pin stack and the rolled stack. The experimental procedure was similar to that used by Castro (1993) in order to be able compare the results obtained in his thesis to those obtained in this thesis. The high temperature source is a heater which holds the hot heat exchanger near room temperature, while the low temperature reservoir is a dewar filled with liquid nitrogen in which the cold end of the prime mover is submerged. The comparison of the acoustic pressures produced and the efficiencies obtained for both stacks was then completed with nearly identical prime mover configurations.

II. THEORY

Thermoacoustic prime movers use the heat flow from a high temperature source to a low temperature sink to produce acoustic power. In this experiment the temperature gradient was externally imposed by holding the hot end at ambient temperature while submerging the cold end in liquid nitrogen. Heat exchangers are placed in the resonator at either end of the stack. The hot heat exchanger is in thermal contact with the high temperature source, while the cold heat exchanger is in thermal contact with the low temperature reservoir. The stack is placed in between the two heat exchangers and is made of a high heat capacity material, relative to the heat capacity of the fluid, to support a smooth temperature profile between the heat exchangers. Both the stack and the heat exchangers need to be relatively open to the gas flow.

The heat exchangers and stack are placed in the resonator at a location where both the acoustic pressure and acoustic displacements are non-zero (Swift, 1995). In a uniform cross sectioned resonator which is closed at both ends, the frequency of the lowest mode of the standing wave produced will be such that the wavelength will be twice the resonator length, or $L = \frac{\lambda}{2}$. There will be pressure antinodes at either end of the tube and a displacement antinode in the center. The hot heat exchanger is placed nearest the pressure antinode and the cold heat exchanger nearest the displacement antinode.

With this configuration the average acoustic pressure amplitude will be larger at the hot end of the stack than at the cold end. The relationship between the change in pressure and the change in temperature in a oscillating wave is given by the expression (Swift, 1988)

$$\frac{T_o}{T_m} = \frac{\gamma-1}{\gamma}\frac{P_o}{P_m}, \qquad (1)$$

where γ is the ratio of specific heats ($\gamma = \frac{5}{3}$ for ideal monatomic gases) and the subscript o indicates the oscillating acoustic value while m indicates the mean value of the pressure or temperature.

The temperature gradient is defined as $\nabla T_m = \frac{T_h - T_c}{\Delta x}$, where T_h is the temperature of the hot end of the stack, T_c is temperature of the cold end of the stack and Δx is the stack length. In a prime mover this gradient is large enough so that the temperature difference of the stack surface seen by an oscillating gas parcel is greater than that due to the temperature change produced by the pressure change in the acoustic oscillations as in equation 1. When a parcel of gas is near the hot end of the stack its temperature is less than the surface and it absorbs heat from the surface which causes it to expand while the pressure is high. A parcel of gas near the cold end of the stack gives up heat to the stack surface and contracts while the pressure is low. Through this process the parcel of gas delivers net work to its surroundings as acoustic power.

For the gas to exchange heat with the surface of the stack it must be close enough to the surface. The thermal penetration depth is roughly the distance that heat can diffuse through the medium during a time $1/\pi f$, where f is the frequency of the acoustic wave. The thermal penetration depth is given by

$$\delta_\kappa = \sqrt{\frac{2K}{\omega \rho_m c_p}} \,. \tag{2}$$

Here K is the thermal conductivity, ρ_m is the mean gas density and c_p is the isobaric heat capacity. Fluid which is within about $1.9\delta_\kappa$ (Swift, 1993) of a stack surface is thermally active and contributes to the production of acoustic power.

Another important quantity is the viscous penetration depth which is defined as

$$\delta_v = \sqrt{\frac{2\mu}{\omega \rho_m}} \,, \tag{3}$$

where μ is the dynamic viscosity. The viscous penetration depth is approximately the distance that shear diffuses in a time $1/\pi f$. Power is dissipated as viscous shear in the volume of gas within a viscous penetration depth of a stack surface.

Since fluid around a thermal penetration depth of the stack surface contributes to the acoustic power produced, and fluid within a viscous penetration depth of the surface contributes to the power dissipated, it should be possible to maximize the efficiency by maximizing the ratio of the thermal volume to the viscous volume. For a parallel plate or rolled stack the volume of fluid within a penetration depth of the stack surface is $\Pi \Delta x \delta$,

where Π is the stack perimeter, or twice the total length of the spirally wound stack if it were unrolled. The ratio of the thermal volume to viscous volume is then $\delta_\kappa/\delta_\upsilon$.

For a pin stack array, with pins of negligible radius aligned with the acoustic axis, the volume within a penetration depth of the stack surface is the number of pins times $\Delta x(\pi\delta)^2$. The ratio of the volume within a thermal penetration depth of a stack surface to the volume within a viscous penetration depth is then $(\delta_\kappa/\delta_\upsilon)^2$.

In neon at P_m=50kPa, T_m=193K, and f=165Hz, application of equations 2 and 3 yields a thermal penetration depth of 0.33mm and a viscous penetration depth of 0.27mm. These parameters are typical of the operating conditions in the prime mover used in this experiment. Since the ratio $\delta_\kappa/\delta_\upsilon$ is greater than 1, it can be seen that the volume ratio for a pin stack array which goes as $(\delta_\kappa/\delta_\upsilon)^2$ is greater than that for a parallel plate stack, which is proportional to $\delta_\kappa/\delta_\upsilon$.

The design of the pin stack is presented in the thesis "Comparison of a Pin Stack to a Conventional Stack in a Thermoacoustic Prime Mover" by F. Scott Nessler (1994). A wire diameter of 0.003 inches ($2r_i = 76\mu m$) was chosen with a hexagonal lattice spacing of $2y_o = 746.8\mu m$ from pin center to pin center. The geometry of this arrangement can be seen in Figure 1 which was copied from Nessler's thesis.

Nessler utilized the program DeltaE (Ward,1993) to compare the predicted performance of the pin stack to a conventional rolled stack. The prime mover parameters used in the computer simulations matched the parameters for the prime mover used in the actual experiment. Nessler obtained results which predicted that the efficiency of the pin stack in this prime mover would be greater than that for a rolled stack (Castro, 1993). Figure 2 shows a chart of the percent Carnot efficiency generated from the results of Nessler's DeltaE simulations. The chart shows that the peak efficiency of the pin stack should be about 1.5 times greater than the peak efficiency of the rolled stack.

The efficiency of the prime mover is W'/Q' (Wheatley 1986), where W' is the work flux or acoustic power delivered by the stack and Q' is the heat flux in. The percent Carnot efficiency is the efficiency divided by the Carnot efficiency $\left(\frac{T_h-T_c}{T_h}\right)$.

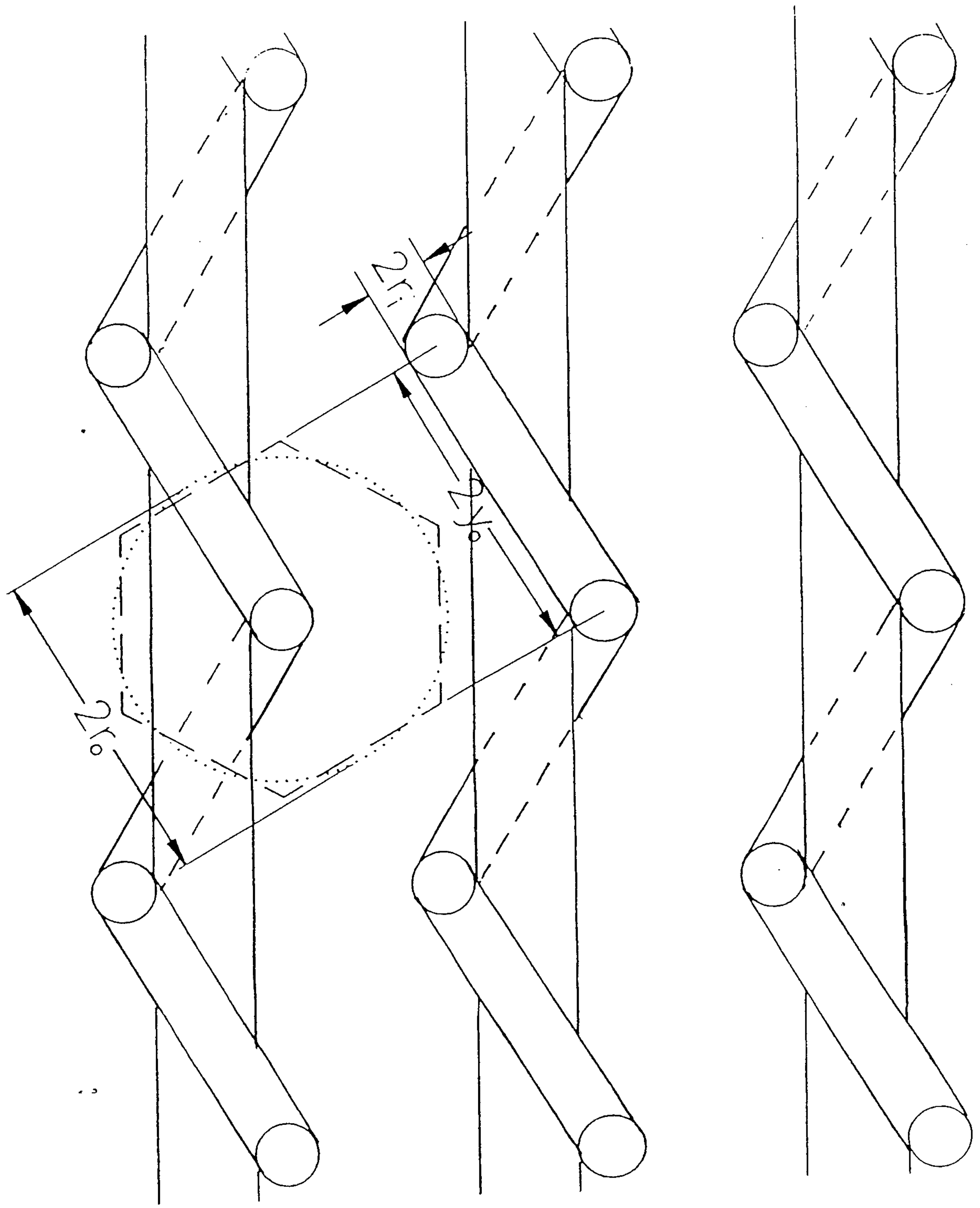


Figure 1. Pin Stack Geometry, from Nessler(1994).

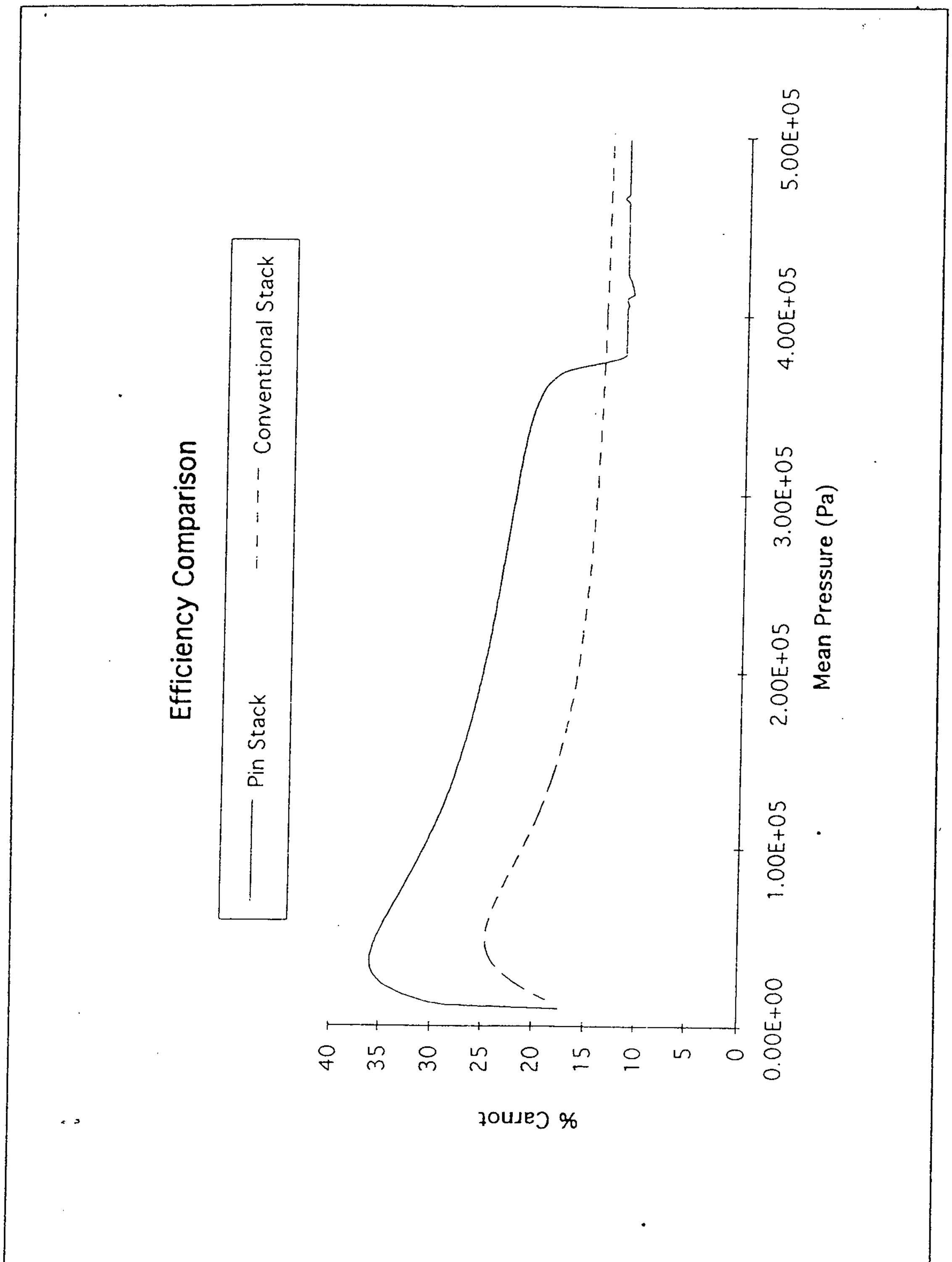


Figure 2. DeltaE Efficiency Comparison, from Nessler(1994).

The quality factor of the resonator can be expressed as 2π times the energy stored divided by the energy lost per acoustic cycle. The value of Q can give an idea of the amount of dissipation losses present. Also, $1/Q=0$ for the prime mover right at onset (Atchley, 1992). Therefore measuring the quality factor can aid in accurately determining where onset will occur.

III. CONSTRUCTION OF PIN STACK

The steps taken in the construction of the pin stack shell are described in the thesis by Nessler (1994). Figure 3 shows a photograph of the completed pin stack. The copper heat exchangers are 3.78 cm in diameter and are 0.82 cm in length. The fins in the heat exchangers are 0.023 cm thick and have a gap of 0.052 cm between them. The heat exchangers are soldered into copper heat exchanger holders which have an outside diameter of 7.366 cm, an inside diameter of 3.967 cm and are 0.953 cm in length.

A glass cylinder separates the hot and cold heat exchanger assemblies and surrounds the pins. Teflon seals were placed between the glass and heat exchanger holders to maintain the seal and allow for differential contraction between the copper and glass. Four equally spaced threaded rods pass through the heat exchanger holders on the outside of the glass cylinder. Beleville Spring washers on the rods maintain a constant force on the Teflon seals during thermal expansion and contraction.

The pins in the stack are constructed from 75 μm constantan wire wound between the hot and cold heat exchangers 2312 times. To maintain the proper spacing on the wires, the copper heat exchanger fins have notches cut in them. The wire sits inside these notches which keeps them in a hexagonal pattern with 750 μm spacing, shown in Figure 1.

Winding of the wire into the pin stack was completed with the use of a jig which held the stack in place while positioning the wire to go into the correct slot on the heat exchanger fin. The jig also held uniform tension on the wires. The wire was soldered to a spring steel needle to allow it to be threaded between the two heat exchangers.

To keep from working with too long of a length of wire, a length of wire long enough to cover one fin was cut. This length of wire was fed through the stack from the cold heat exchanger side to the hot side. The wire was then tied and super glued into the slot closest to the shell wall on the hot heat exchanger fin. The wire was then wound between the hot and cold heat exchanger fins towards the opposite wall. Upon reaching the opposite shell wall the wire was again tied and super glued into the slot nearest the wall on the heat exchanger fin.

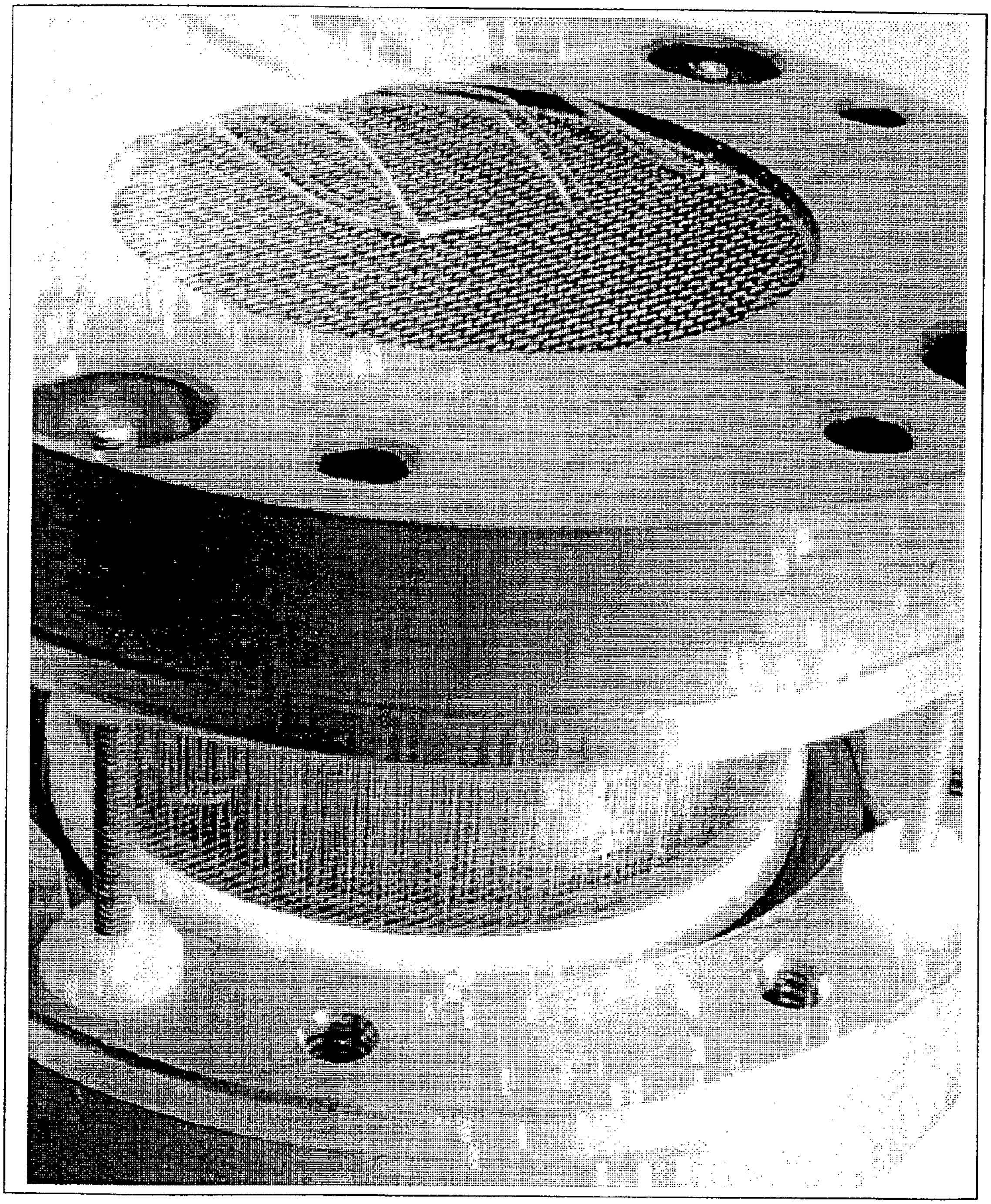


Figure 3. Pin Stack.

Using glass for the enclosure around the pins allowed the winding process to be viewed. This made the fixing of errors that occurred while winding easier. Even with the use of the jig the wire would occasionally go into the wrong slot or would not go into a slot at all. If these errors were observed prior to the next pass of the wire being taken through the heat exchangers, they could be fixed. If an error could not be repaired it was logged in an attempt to keep track of the overall number of errors.

If a wire did not go into the proper slot, the distance to neighboring wires was different than the desired 750 μm. Also the wire would not be aligned with the acoustic axis of the tube. The total number of errors was 74. A wire going to a slot neighboring the desired slot was counted as one error. A wire going over top of the fin but near its desired slot was counted as a half error. Since there are 1,156 slots on each heat exchanger the error percentage is $\frac{74}{2*1156} * 100 = 3.2\%$.

Figure 4 shows a wire that is not positioned properly. The arrow in the figure points to a wire that has gone into the wrong slot on the bottom heat exchanger. While the wire position is wrong near the heat exchanger fin where it went into the wrong slot, it is in the proper position at the opposite heat exchanger fin.

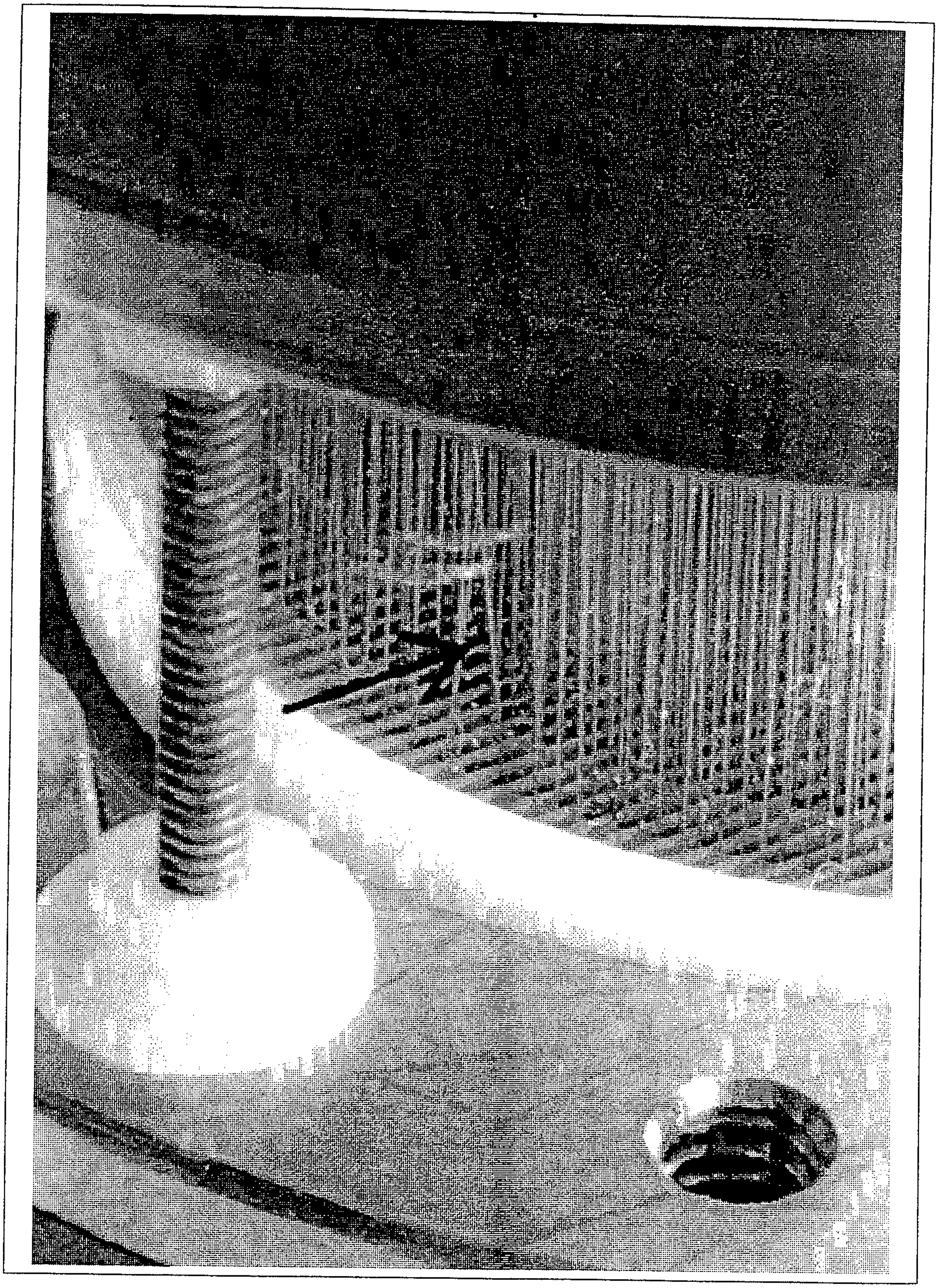


Figure 4. Pin Stack Winding Error.

IV. EXPERIMENTAL PROCEDURE

A. THERMOACOUSTIC PRIME MOVER

A complete description of the prime mover used in this experiment can be found in the thesis "Experimental Heat Exchanger Performance in a Thermoacoustic Prime Mover" by Nelson Castro (1993). The line drawing of the prime mover shown in Figure 5 was obtained from Castro's thesis. The experiment was performed first with the heat exchangers and rolled stack described in Castro's thesis, then with the pin stack.

Two modifications were made to the prime mover for this experiment. First a speaker was mounted by Nessler to the bottom surface of the moveable plunger. The speaker consists of a piezoelectric disk mounted to a cylinder with a diameter of 2.26 cm and a length of 0.94 cm. The speaker was glued to the plunger with three 0.36 cm compliant blobs of silicone adhesive. The resonant frequency of the speaker measured in air at atmospheric pressure is 3442.6 Hz.

The second modification to the prime mover was the addition of a thermocouple flange (see appendix A for specifications) which allows thermocouple leads to conveniently pass outside the prime mover without having a tangled wad of wire in the acoustic space. This flange was inserted between the upper tube attachment plate and the hot heat exchanger holder. The flange has an outside diameter of 9.906 cm and an inside diameter of 3.772 cm. Eight bolt holes in the thermocouple flange line up with the bolt holes in the upper tube attachment plate. The wires pass through a 0.635 cm radial hole in the flange, and through a tube soldered into the hole, and then are pulled tight. After the thermocouple wires were passed through the tubing, high temperature vacuum wax was melted into the tubing around the wires to seal the flange against air leaking into the neon gas inside the prime mover. The wires were partially stripped inside the wax to seal the leak between the wire and their insulation.

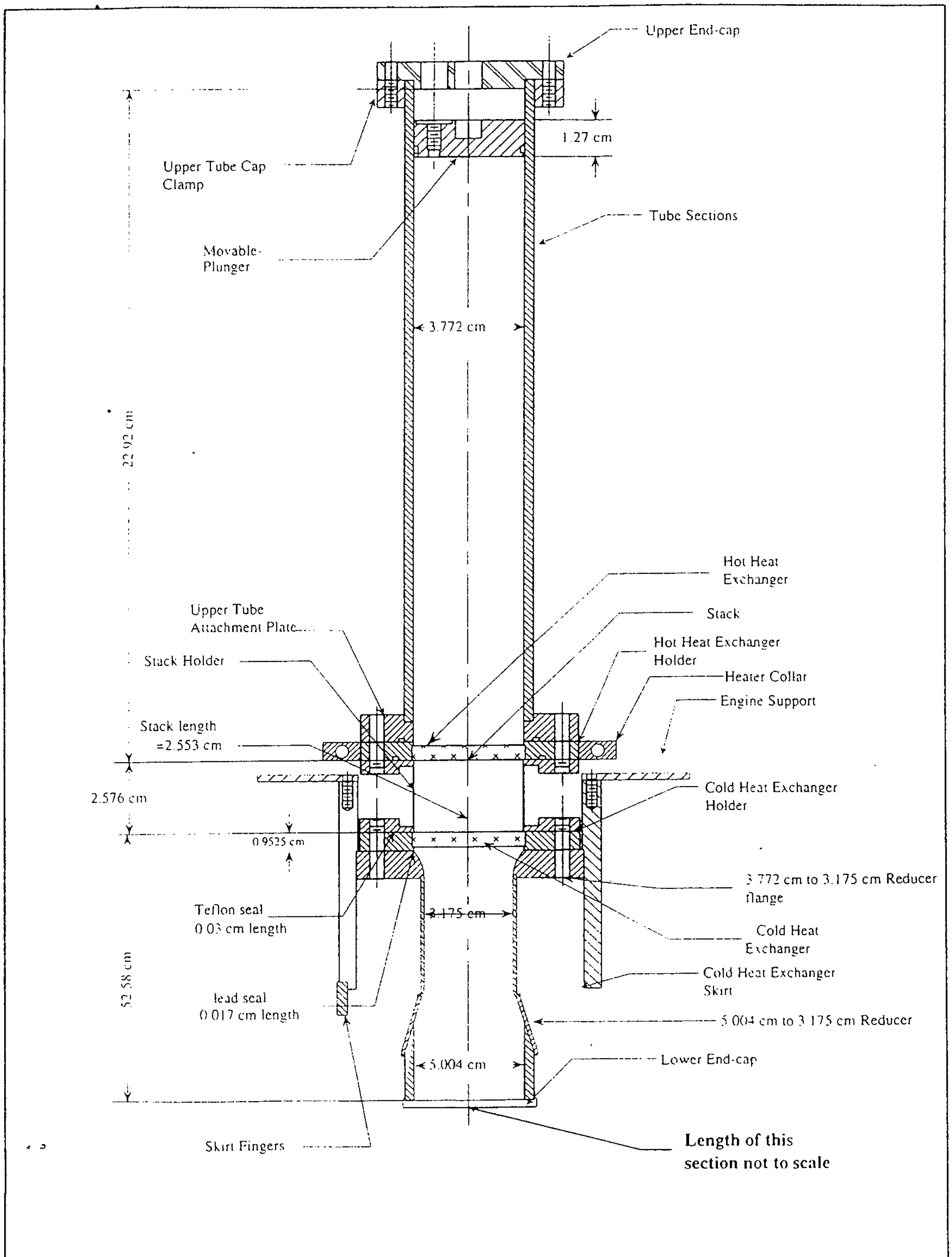


Figure 5. Thermoacoustic Prime Mover, from Castro(1993).

A rubber plug was inserted into the hole where the wires pass through the inner diameter of the flange. This plug forms an acoustic seal between the inside of the prime mover and the brass tubing. A capillary tube was inserted between the acoustic plug and the wax seal. This capillary tube was connected to the fill tube to ensure that the gas in the volume between the acoustic plug and the wax seal would be pure neon after the purging process.

B. INSTRUMENTATION

Figure 6 shows a block diagram of the instrumentation used in this experiment. The temperatures of the prime mover were monitored with type E thermocouples. Four thermocouples went through the thermocouple flange into the inside of the prime mover. The placement of these thermocouples can be seen at the top of Figure 3. They were secured to the center fin of both heat exchangers with silver epoxy. One was placed at the inside wall of the heat exchanger holder, and the other was placed at the center of the fin.

Four additional thermocouples were placed on the outside of the prime mover. One was mounted to the hot tube wall 9.5 cm above the upper tube attachment plate. Another was placed in a slot in the heater collar between the collar and the outside surface of the hot heat exchanger holder. A third was attached to the cold heat exchanger skirt which was submerged in liquid nitrogen. The last thermocouple was used as feedback for temperature control of the heater collar and was mounted to the bolt that secured the collar to the heat exchanger holder.

All of the thermocouples except the one used for the temperature controller were monitored by a Keithly Model 740 scanning thermometer. The output from the thermometer was recorded by a personal computer. The computer saved the results in a file for later analysis.

Temperature control of the heater collar was managed by an Omega Model CN9000 temperature controller. The analog output of the temperature controller was fed to a Techron Model 5530 power supply amplifier. The power supply amplifier provided

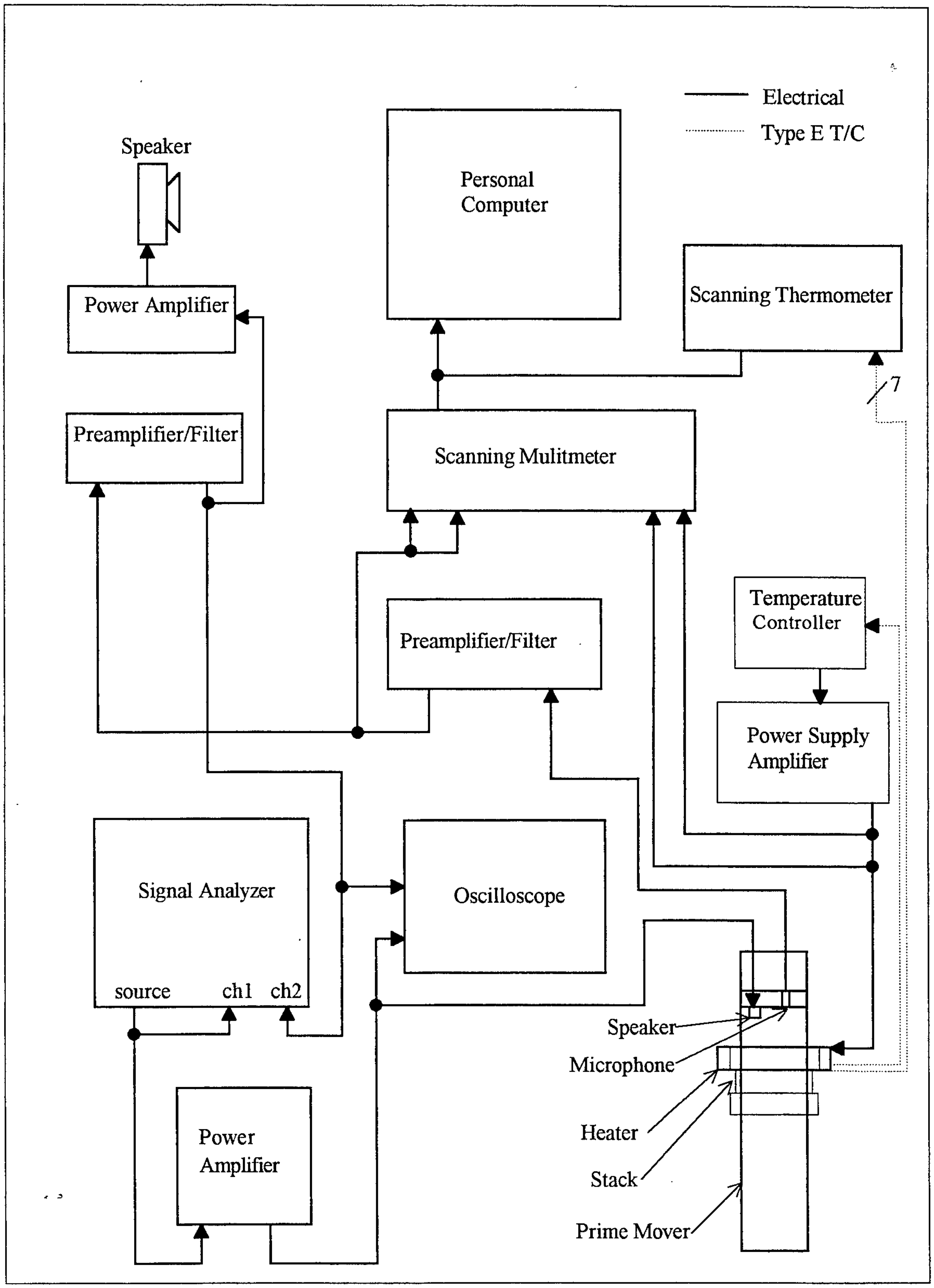


Figure 6. Measurement Set-up.

the power to the heater cartridges in the heater collar through a 0.2 Ω resistor. The voltage drop across the resistor was measured enabling the current into the heater cartridges to be computed. Also the voltage on the heater side of the resistor was measured. Both the voltage and current measurement were monitored by a Hewlett-Packard Model 3457A scanning multimeter and passed on to the computer. The product of the values of the current and voltage is the power to the heater cartridges.

The mean and acoustic pressures inside the prime mover were measured with an Endevco Model 8530C-15 microphone. The microphone sensitivity was 16.38 mV/psi and the zero pressure reading was -10.22 mV. The microphone output is sent to a custom preamplifier with a gain of 9.927 and a 32 kHz low-pass filter. The output from the preamplifier was sent to the scanning multimeter. The scanning multimeter measured both the AC and DC signals from the microphone. The AC voltage gives the acoustic pressure while the DC voltage gives the mean pressure.

The signal out of the custom preamplifier was also sent to a Stanford Research Model SR560 preamplifier with a high-pass filter of 1 Hz, a low pass filter of 30 kHz, and AC coupling selected. This microphone signal was monitored on a Tektronix Model TDS 420 oscilloscope, and also routed to a loudspeaker via a Techron Model 5507 power supply amplifier. The oscilloscope allowed the waveform of the microphone to be observed.

The microphone signal out of the SR560 preamplifier was also routed to channel 2 of a Hewlett-Packard Model 3562A dynamic signal analyzer. In addition to measuring the frequency spectrum of the microphone output, the signal analyzer was used as a source for the piezoelectric speaker in the prime mover. The source signal was connected to channel 1 of the analyzer to allow the frequency response between the speaker and the microphone be measured, thus enabling the Q of the resonator to be determined below onset. The source signal was boosted with a gain of five by a Hewlett-Packard Model 467A power amplifier prior to going to the speaker.

C. PROCEDURE

The moveable plunger allowed the stack position relative to the end of the resonator to be adjusted. The experiment was performed for two different plunger positions. In order to be able to compare the experimental results with those from the previous experiment (Castro, 1993), it was decided to use the same plunger positions. The positions given specified the distance from the lower face of the moveable plunger to the hot end of the stack. These distances were 8.13 cm and 10.66 cm.

To compensate for the volume taken up by the speaker inside the prime mover, the plunger distance was lengthened by an amount such that the area of the tube times the change in length equaled the volume of the speaker. This increased the distances by 0.13 cm. The plunger distances will still be referred to as the 8.13 cm and 10.66 cm plunger positions throughout this report, however.

After assembling the prime mover and prior to replacing the air with neon, quality factor measurements were taken at room temperature. This was done for the rolled stack at the 8.13 cm plunger position, and for the pin stack at both plunger positions.

The measurements were taken by driving the speaker inside the prime mover with a 5.0 Vpk random noise source from the dynamic signal analyzer with a gain of five on the amplifier. The gain on the SR 560 preamplifier was set to 10^4. The frequency response between the speaker and the microphone was then obtained with the signal analyzer. Stable-mean averaging was used to smooth out the response.

After a frequency response measurement was taken, the curve fitting function of the signal analyzer was utilized to determine the resonance frequency and quality factor of the resonator. The analyzer uses pole-zero analysis to complete its curve fit. The poles were given as a complex number of the form a+jb. The resonant frequency is $f = \sqrt{b^2 + a^2}$, and the quality factor is $Q = \sqrt{b^2 + a^2}/(-2a)$. These values were verified by observing the peaks and the -3 dB points on the frequency response display.

Initially a frequency span from 0 Hz to 1.5 kHz was used to determine frequency and Q for each of the first five resonances. It was determined however, that a more accurate measurement could be taken if the frequency span was reduced in order to obtain

more data points around the resonant frequency. The frequency response was then taken with the fundamental resonance as the center frequency and a frequency span of 200 Hz.

The next step was to purge the air out of the prime mover and replace it with neon. This was accomplished by pumping down the mean pressure with a vacuum pump to 14 kPa then refilling it with neon to 110 kPa. The purging process was repeated five times.

After removing the air from the prime mover, the pressure was reduced to about 3 kPa to ensure that it would be below onset once the lower end was cooled by filling the dewar with liquid nitrogen. When the cold end of the prime mover reached liquid nitrogen temperatures and prior to reaching onset, the heater power was checked to determine the heat leak from the warm end to the cold end. The temperature controller set point temperature was set to 35° C.

Next the quality factor measurements were taken for several mean pressures below onset. The process for taking these measurements was the same as that for the measurements taken in air at room temperature. The mean pressure had to be increased to over about 4 kPa to obtain a clean enough frequency response to complete the measurement.

Upon completing the Q measurements the mean pressure was slowly increased until the prime mover went into onset. Above onset the mean pressure was increased up to 50 kPa with the rolled stack and 90 kPa with the pin stack. The mean pressure was stabilized periodically to allow the prime mover to reach steady state. The computer kept a log file of the frequency, temperatures, pressures and heater power throughout the experiment. At each point where the mean pressure was stabilized the frequency response was obtained and the temperature and pressure values were recorded in a log book as a back up to the computer file.

With the rolled stack for both the 8.13 cm plunger position and the 10.66 cm plunger position, the mean pressure was swept up to its maximum value and down below onset twice to ensure repeatability in the experiment. The frequency was monitored to

ensure gas purity. An air leak would cause the frequency to shift downward at equivalent mean pressures and prime mover temperatures.

After the experiment was completed with the rolled stack, the prime mover was assembled with the pin stack in place. Upon leak checking the prime mover it was determined that the pin stack had a slow leak around the joint where the glass, Teflon, and copper meet. To repair this a bead of silicon was placed in this area. This decreased the leak further but did not eliminate it.

A stainless steel shell was constructed around the pin stack between the hot and cold heat exchanger flanges, and sealed with automobile gasket sealing compound (Permatex #9A). Neon flowed into the shell through a fill tube in the shell, and passed through the shell out through a vent tube on the opposite side. The flow of neon was monitored by bubbling the flow from the vent tube into a beaker of pump oil. The shell may not have made a perfect seal, but since it was kept just over atmospheric pressure, the gas purity inside was maintained while keeping a continuous flow of neon into the shell. The mass flow rate of neon was measured by interrupting the flow into the fill tube and watching the rate that pump oil was drawn back into the vent tube. This mass flow rate of neon matched the initial leak rate into the prime mover, measured by monitoring the mean pressure increase inside the resonator. The result was that gas leaking into the inside of the prime mover was pure neon from the shell. An open celled foam insulation was placed between the shell and the stack to decrease the heat leak in this space.

The experiment was then completed for the pin stack. Measurements were taken at both the 8.13 cm and 10.66 cm plunger positions. The frequency was carefully monitored throughout the experiment to ensure gas purity.

V. RESULTS AND DISCUSSION

A. QUALITY FACTOR MEASUREMENTS IN AIR

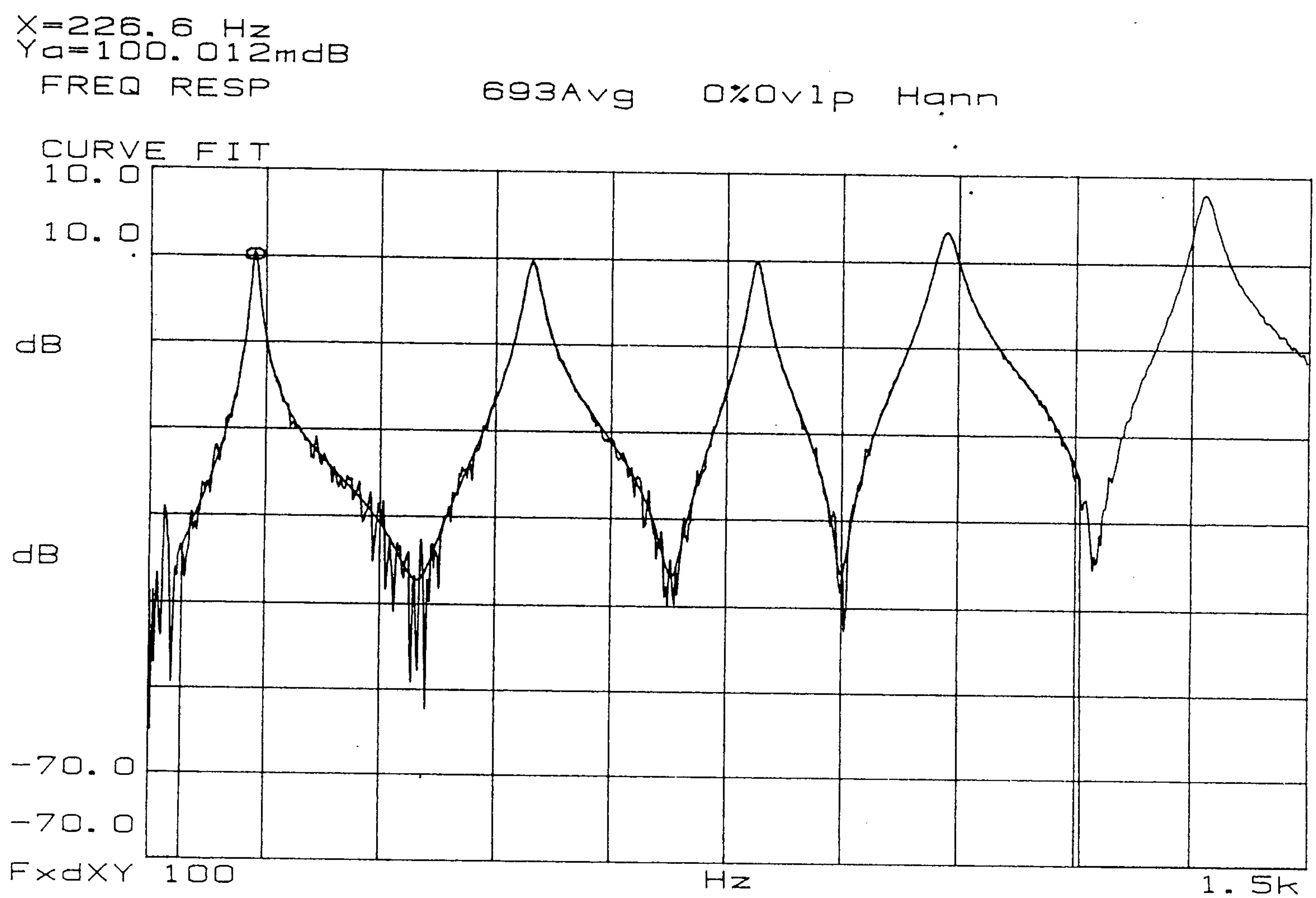
A Q measurement was taken at the 8.13 cm plunger position with the conventional rolled stack installed in the prime mover . The prime mover contained air at P_m=101.3 kPa and a uniform temperature of 20.3° C. For the first mode the measured values were f=229.4 Hz and Q=24.6. For the second mode the values were f=554.3 and Q=24.0. The Q measurements in air were not taken at the 10.66 cm plunger position for the rolled stack.

Q measurements for the pin stack were also taken at both plunger positions in air at room temperature. Figure 7 shows the frequency response at the 8.13 cm plunger position. The smooth line superimposed on the data for the first four resonance peaks is the curve fit that the signal analyzer calculated with its pole-zero analysis. It can be seen that curve fit is an accurate representation of the data in this region.

In these measurements the mean pressure was 102.0 kPa and the temperature was 21.9° C. With the frequency span reduced to 200 Hz centered on the first resonance the measurement was taken again. The resulting values for the first resonance were f=227.3 Hz and Q=29.1. The procedure was repeated for the 10.66 cm plunger position with the same mean pressure and temperature. The first resonance frequency was 217.0 Hz and Q was 26.8.

Comparing the quality factor of the pin stack to the rolled stack at the 8.13 cm plunger position it can be seen that the Q is larger for the pin stack. This is consistent with the losses due to dissipation in the stack being less for the pin stack. The ratio of the Q's is $Q_{pin}/Q_{rolled} = 29.1/24.6 = 1.18$. Another conclusion to be made is that since the Q is higher for the pin stack at the 8.13 cm plunger position than the 10.66 cm plunger position the dissipation losses are less at the closer position. This is consistent with the results obtained above onset.

The program DeltaE (Ward, 1993) was used to develop a predicted frequency response for the prime mover with the pin stack at the 8.13 cm plunger position. The temperature, mean pressure and prime mover geometry in the program were fixed at the



Pin Stack in Air, 8.13 cm Plunger Position

Figure 7. Pin Stack in Air Frequency Response.

measured values in the experiment for air at room temperature. The speaker was simulated by imposing a volume velocity at the plunger. The frequency in the program was the swept from 200 to 1100 Hz. Figure 8 is the output from the program where the dB on the vertical scale is calculated by $20\log(P_o/P_{o,max})$, where $P_{o,max}$ is the maximum acoustic pressure. DeltaE gives Q's which are about twice the measured values.

B. QUALITY FACTOR MEASUREMENTS BELOW ONSET

After replacing the air in the prime mover with neon, the cold section was cooled by filling the dewar with liquid nitrogen. Quality factor measurements were taken at various mean pressures below onset. The procedure for taking these measurements was the same as that for the Q measurements in air. The cold heat exchanger temperatures were held at -192° C and the hot heat exchanger temperatures were held at 35° C. The heater power was also noted below onset to estimate the heat leak.

The results of measurements taken for the rolled stack at the 8.13 cm plunger position can be seen in Figure 9. The plot shows 1/Q versus mean pressure. The prime mover starts producing sound, goes into onset, when 1/Q=0 or Q approaches infinity. The mean pressure was varied between 3.8 and 9.4 kPa where onset was achieved. The heater power was 14.3 watts while taking these measurements.

The measurements were also taken for the rolled stack with the 10.66 cm plunger position. The results of are shown in Figure 10. Here the prime mover went into onset at 10.1 kPa. Care had to be taken near onset to keep the temperatures constant. If the liquid nitrogen level was not held very near the top of the dewar, the temperatures of the cold heat exchangers would begin to rise. Subsequently increasing the liquid nitrogen level could precipitate onset due to the increased temperature gradient across the stack without changing the mean pressure. The heater power was 15.0 watts during these measurements.

With the pin stack installed into the prime mover the Q measurements were again attempted. When the pin stack was cooled to liquid nitrogen temperatures the leak rate around the Teflon seal increased presumably due to differential contraction. The shell

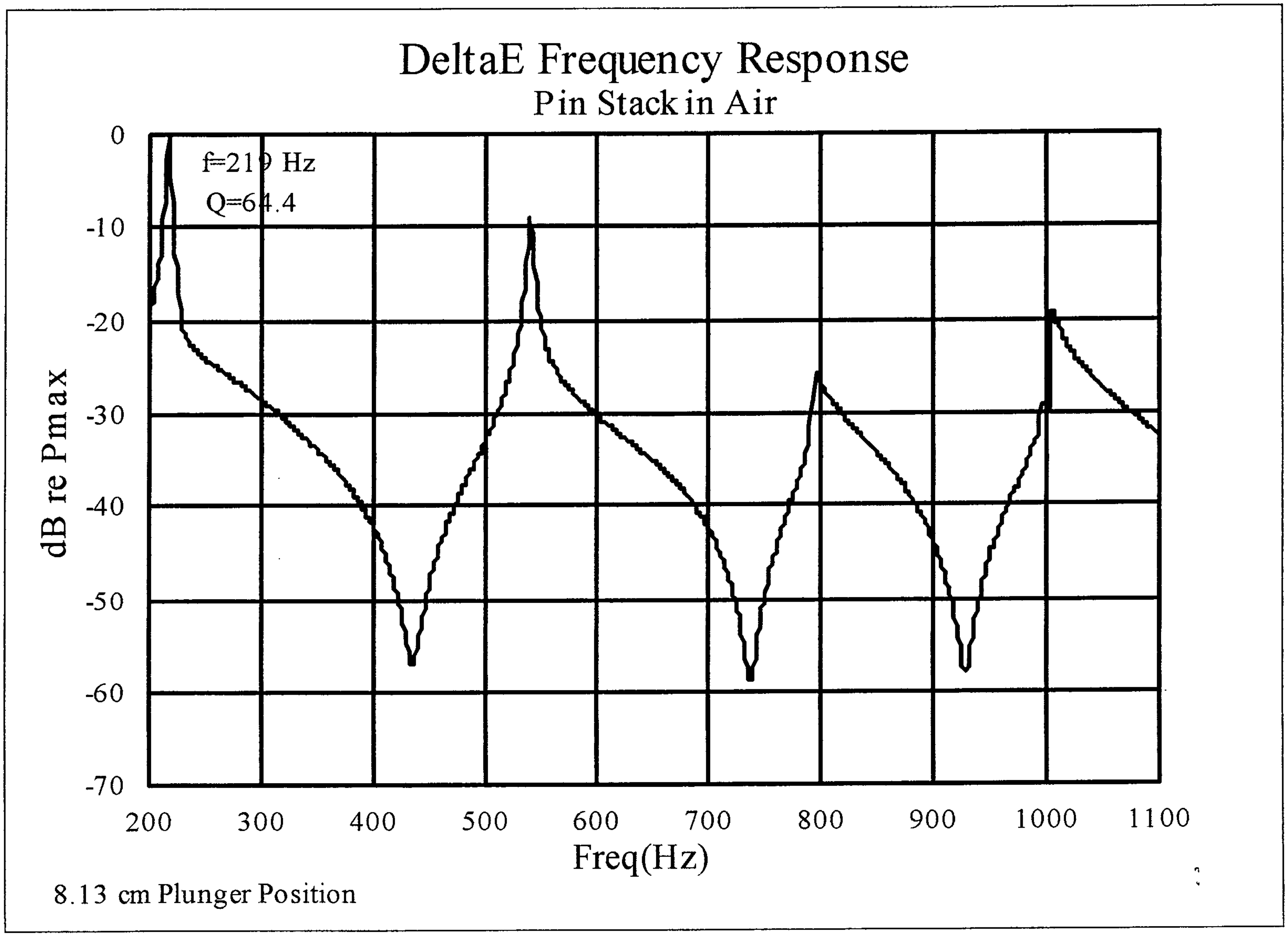


Figure 8. DeltaE Predicted Frequency Response.

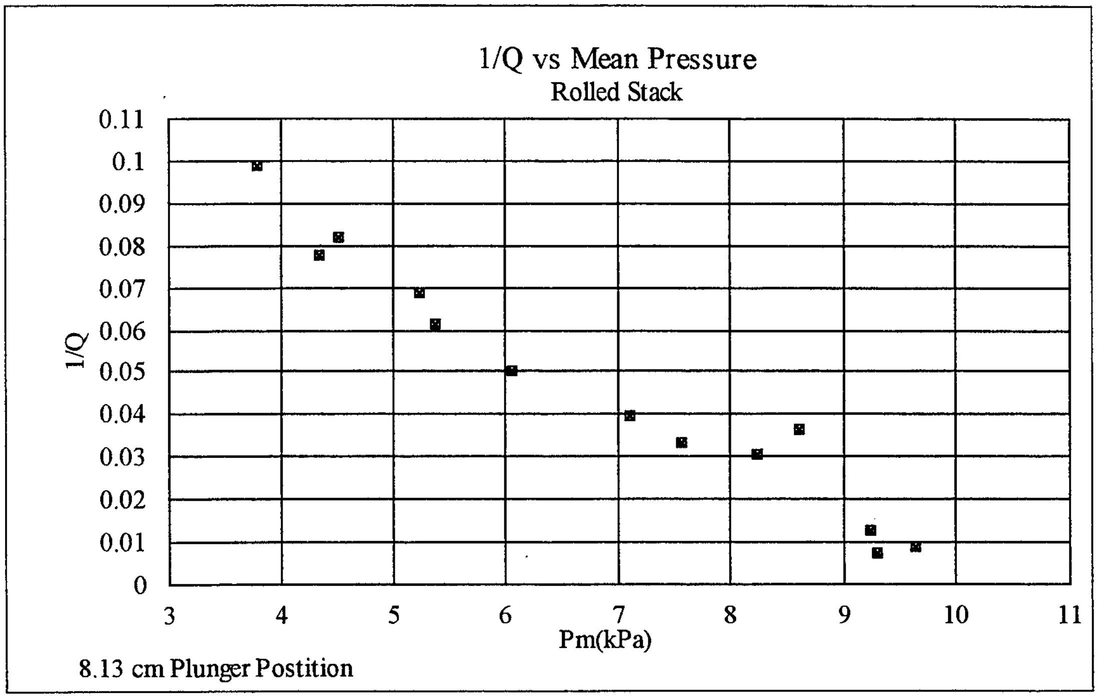


Figure 9. Rolled Stack 8.13 cm Q Measurement Results.

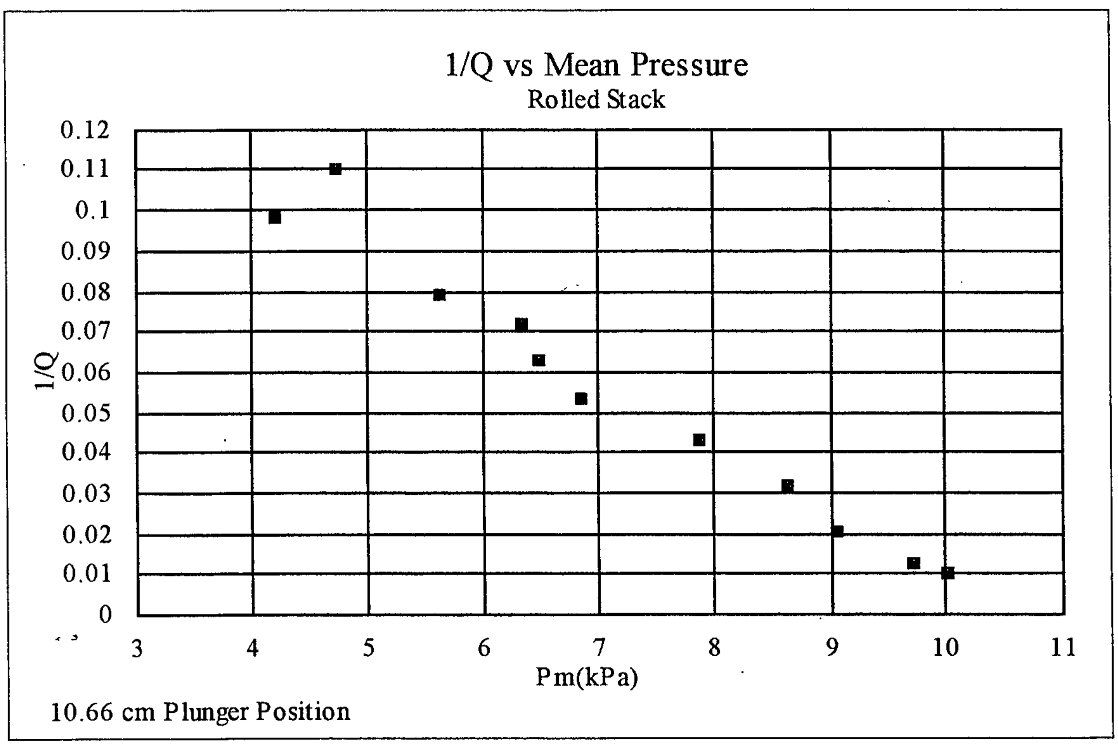


Figure 10. Rolled Stack 10.66 cm Q Measurement Results.

around the stack was filled with neon at just over atmospheric pressure to ensure that the gas leaking in was pure neon. However, at the low pressures the leak rate into the stack was greater than the rate that gas could be removed through the capillary fill tube, even while continually pumping on the prime mover. The result was that the low pressures could not be maintained and the pressure inside the prime mover slowly increased to about 20 kPa where it stabilized. The leak rate was generally too fast to allow Q measurement to be taken, but was sufficiently slow to enable the other data to be taken while the mean pressure increased.

Only two Q measurements for the pin stack were taken at the 8.13 cm plunger position. For the pin stack at this plunger position the Q was 38.4 at $P_m = 4.48$ kPa and the Q was 507.4 at $P_m=5.38$ kPa. Comparable values of the Q for the rolled stack at this plunger position were 12.2 at $P_m=4.51$ kPa and 16.4 at $P_m=5.38$ kPa. Onset for the pin stack occurred at $P_m=5.55$ kPa as compared to 9.4 kPa for the rolled stack.

No Q measurements could be obtained for the pin stack below onset at the 10.66 cm plunger position. Onset occurred at Pm=6.57 kPa for the pin stack at this plunger position compared to Pm=10.1 kPa for the rolled stack.

It can be seen that the quality factors were greater for the pin stack than for the rolled stack. Also the mean pressure at which onset occurred was lower for the pin stack at both plunger positions.

For the pin stack the heater power below onset varied between 35 and 58 watts. The heat conduction through the constantan wires of the pin stack is calculated to be 2 watts and the conduction through the stainless steel shell, described on page 20, should be 7 watts. When adding liquid nitrogen into the dewar, the cold vapor from the boil off contacted the heater collar and increased the heater power from the 35 to 58 watt value. This increased heat leak over the rolled stack values of 14.3 watts, and its dependence on the liquid nitrogen flow, creates a large uncertainty in the efficiency comparison described below. Above onset liquid nitrogen had to be continuously added to keep the cold heat exchangers cold.

C. MEASUREMENTS ABOVE ONSET

Above onset the mean pressure inside the prime mover was slowly varied over a range of pressures to obtain accurate data. The rms acoustic pressure, thermocouple temperatures, frequency, and heater power were recorded while sweeping the mean pressure. The mean pressure was stabilized at selected intervals to allow the prime mover to stabilize and the power spectrum to be recorded with the signal analyzer.

Table 1 contains a summary of the data taken above onset. Results of all four experiments are included. The values in the table are those obtained during the periods when the mean pressure was stabilized to ensure steady state results. The mean pressure values reported for each data set are equivalent to allow comparison between the two stack at both plunger positions. The first line in each data set shows the conditions just below onset.

Rolled Stack, 8.13 cm Plunger Position, Heat Leak Below Onset= 14.3 Watts

Pm(kPa)	%RMS Po/Pm	Cold HX Wall T(C)	Cold HX Ctr T(C)	Hot HX Wall T(C)	Hot HX Ctr T(C)	Hot Tube T(C)	Freq(Hz)	Heater Power(W)
*9.26	0.046	-192.2	-192.2	35.6	35.9	35.2	N/A	14.3
9.98	7.32	-191.2	-191.6	34.3	35.4	35.3	177.51	16.6
14.95	15.71	-182.8	-185.3	23.8	30.0	33.7	173.67	60.1
19.99	18.52	-176.6	-181.3	14.6	25.4	32.4	171.28	92.8
27.81	19.96	-167.7	-175.4	5.9	21.2	31.3	168.56	142.7
49.99	19.22	-153.6	-164.9	-13.5	8.1	23.7	164.74	197.0

Rolled Stack, 10.66 cm Plunger Position, Heat Leak Below Onset=15.0 Watts

Pm(kPa)	%RMS Po/Pm	Cold HX Wall T(C)	Cold HX Ctr T(C)	Hot HX Wall T(C)	Hot HX Ctr T(C)	Hot Tube T(C)	Freq(Hz)	Heater Power(W)
*10.00	0.046	-192.4	-192.4	37.5	37.9	37.3	N/A	15.0
10.90	7.68	-190.2	-190.8	34.3	36.1	36.7	171.89	27.1
14.98	13.13	-182.0	-184.5	25.5	31.7	35.5	169.96	57.3
20.00	15.76	-174.0	-178.9	16.2	27.2	34.4	167.21	85.6
27.81	17.21	-165.8	-174.1	2.7	19.5	31.2	163.58	139.9
50.08	16.50	-152.4	-164.1	-21.2	2.0	20.5	158.73	209.9

*Data taken at a mean pressure just below onset.

Table 1. Summary of Data Taken Above Onset.

Pin Stack, 8.13 cm Plunger Position, Heat Leak Below Onset=58 Watts

Pm(kPa)	%RMS Po/Pm	Cold HX Wall T(C)	Cold HX Ctr T(C)	Hot HX Wall T(C)	Hot HX Ctr T(C)	Hot Tube T(C)	Freq(Hz)	Heater Power(W)
*6.02	0.164	-192.1	-191.9	36.4	36.2	34.3	N/A	58
10.01	15.47	-185.4	-188.1	30.2	33.6	35.4	167.99	86.3
14.95	19.90	-175.1	-181.8	22.9	30.0	35.4	165.61	107.2
20.01	22.52	-170.0	-179.7	19.4	30.2	37.9	164.13	156.5
27.52	23.35	-163.0	-175.1	11.5	27.2	37.9	162.55	196.6
49.93	22.44	-152.9	-167.4	-5.7	19.2	34.3	160.68	254.4
70.09	21.64	-147.9	-162.8	-10.7	19.0	36.5	160.21	301.0
90.19	20.64	-145.8	-160.3	-14.5	17.0	37.6	159.89	311.4

Pin Stack, 10.66 cm Plunger Position, Heat Leak Below Onset=35 Watts

Pm(kPa)	%RMS Po/Pm	Cold HX Wall T(C)	Cold HX Ctr T(C)	Hot HX Wall T(C)	Hot HX Ctr T(C)	Hot Tube T(C)	Freq(Hz)	Heater Power(W)
*6.47	0.306	-189.7	-189.6	30.9	31.0	29.4	N/A	35
10.03	14.23	-183.6	-187.4	23.3	27.5	30.6	162.19	102.2
14.97	18.61	-172.4	-181.0	15.4	24.4	31.5	160.29	130.0
19.94	20.19	-164.6	-176.4	8.9	22.0	32.3	159.10	164.4
27.78	20.92	-156.0	-170.2	0.4	19.0	32.4	157.40	204.9
50.31	19.85	-143.3	-159.7	-13.6	13.0	33.0	155.33	253.9
69.98	18.97	-139.9	-156.4	-20.3	10.0	32.7	154.71	287.5
90.21	18.07	-137.6	-153.9	-24.2	7.8	32.7	154.31	315.6

*Data taken at a mean pressure just below onset.

Table 1. Summary of Data Taken Above Onset(continued).

The first data set gathered was for the rolled stack at the 8.13 cm plunger position. The mean pressure was increased from onset up to 50.6 kPa then pumped back down to below onset and then the process was repeated. This meant that each data point was taken four different times over the course of the experiment.

A plot of the normalized acoustic pressure versus the mean pressure is shown in Figure 11. The normalized acoustic pressure is the rms acoustic pressure divided by the mean pressure. This plot was generated by loading the log file generated by the computer into a spreadsheet. The plot includes all four runs, twice from a mean pressure below onset up to the maximum mean pressure and then back down to below onset.

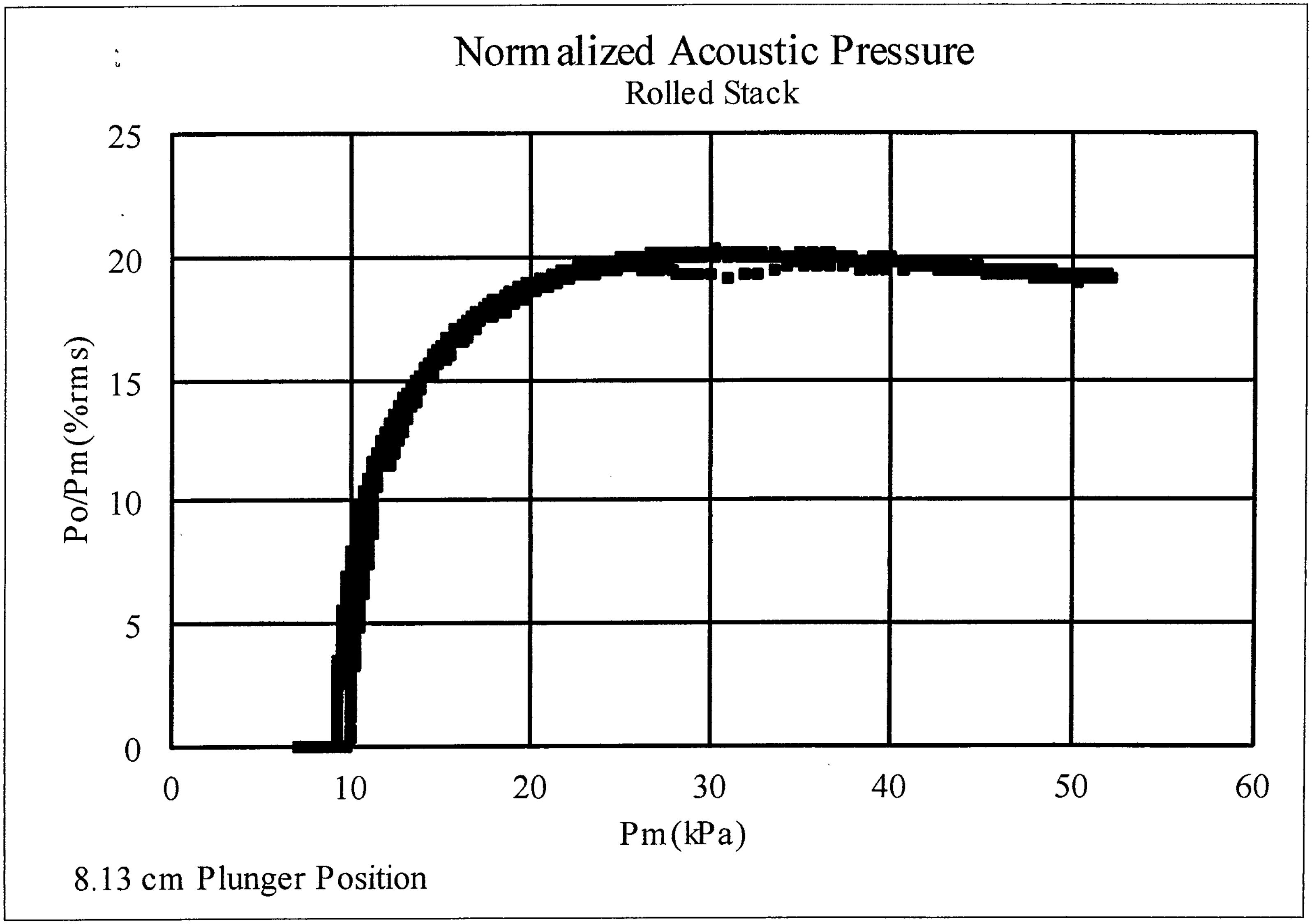


Figure 11. Rolled Stack 8.13 cm Normalized Acoustic Pressure.

Figure 12 shows the temperature difference between the hot and cold heat exchanger. The temperatures T_h and T_c are the average of the wall and center temperatures for the hot and cold heat exchangers respectively. It can be seen that the temperature difference could not be maintained as the mean pressure was increased (Castro, 1993). Also the temperature oscillated at higher pressures because the temperature controller was not stable at the larger powers.

Figure 13 shows the heater power versus mean pressure. The heat leak below onset of 14.3 watts was subtracted from these values. The heater power started oscillating at a mean pressure of about 25 kPa. The amplitudes of the oscillations increased as the acoustic pressures increased. To analyze this data it was necessary to average the heater power during periods where the mean pressure was stabilized to determine the actual heater power. The value of this power was required to complete the efficiency comparison between the rolled stack and the pin stack.

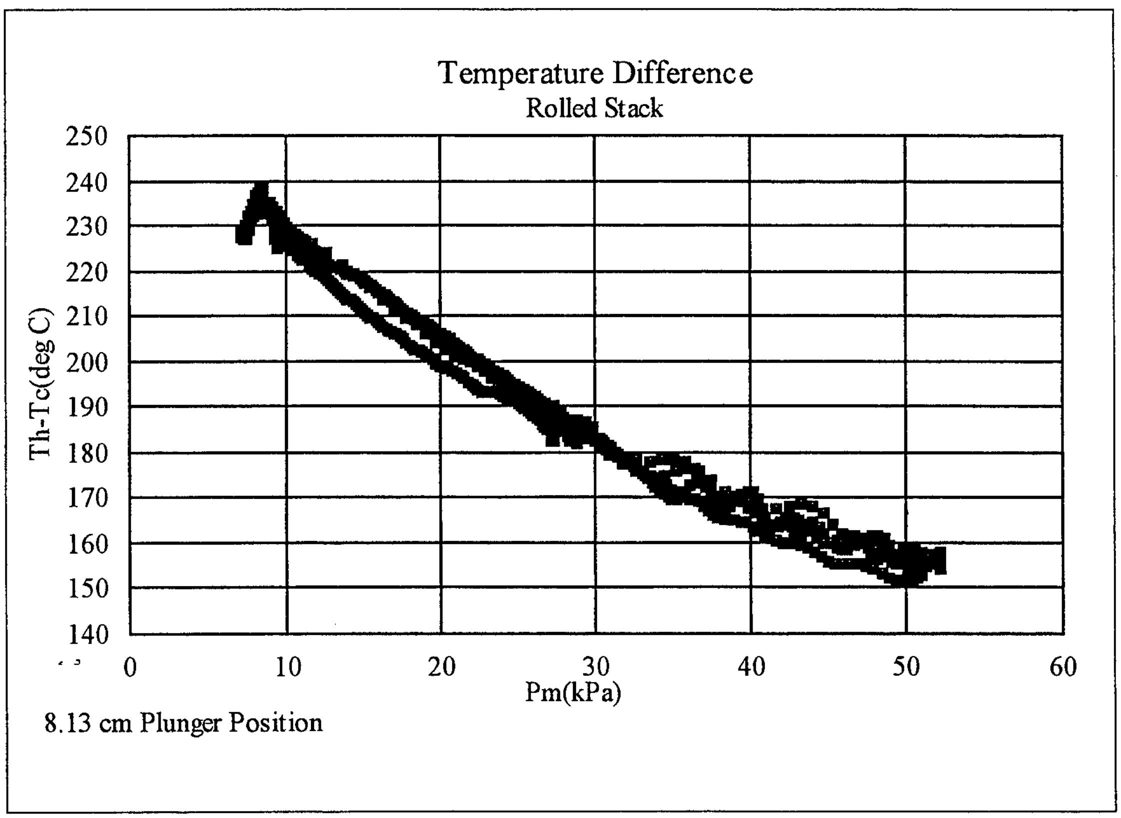


Figure 12. Rolled Stack 8.13 cm Temperature Difference.

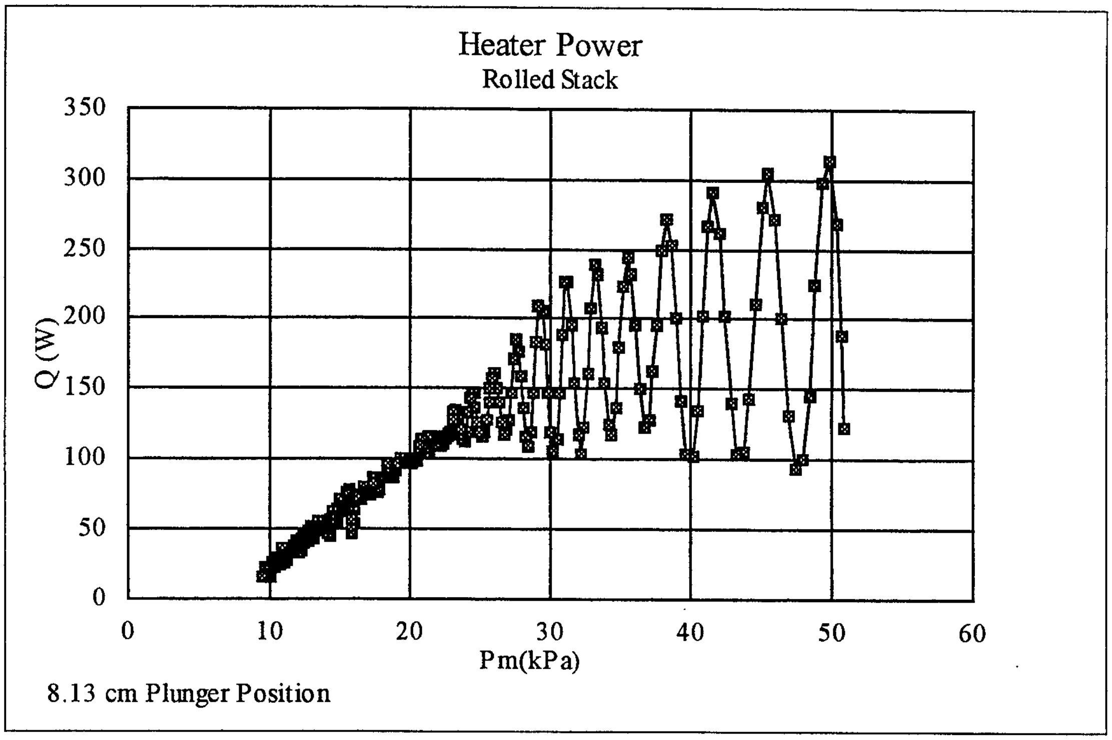


Figure 13. Rolled Stack 8.13 cm Heater Power.

After taking the data at the 8.13 cm plunger position the plunger was moved to the 10.66 cm position. The procedure described above was repeated for the rolled stack in the new plunger position. Prior to completing the second run at the 10.66 cm plunger position, a circuit that took the square root of the input signal was wired in series between the temperature controller and the power supply amplifier. The output of this circuit was $V_{out} = 0.268\sqrt{10V_{in}}$, where V_{in} is the voltage from the controller and V_{out} is the voltage to the power supply amplifier. Since the heater power goes as the square of V_{out}, the circuit's effect is to keep the temperature controller loop gain constant over the range of heater powers. The circuit greatly reduced the oscillations of the heater power at the higher acoustic pressure amplitudes enabling a more accurate determination of the actual heater power.

The normalized acoustic pressure versus the mean pressure for the rolled stack in the 10.66 cm plunger position can be seen in Figure 14. The data plotted is for one sweep up in pressure then back down to below onset after the square root circuit was installed.

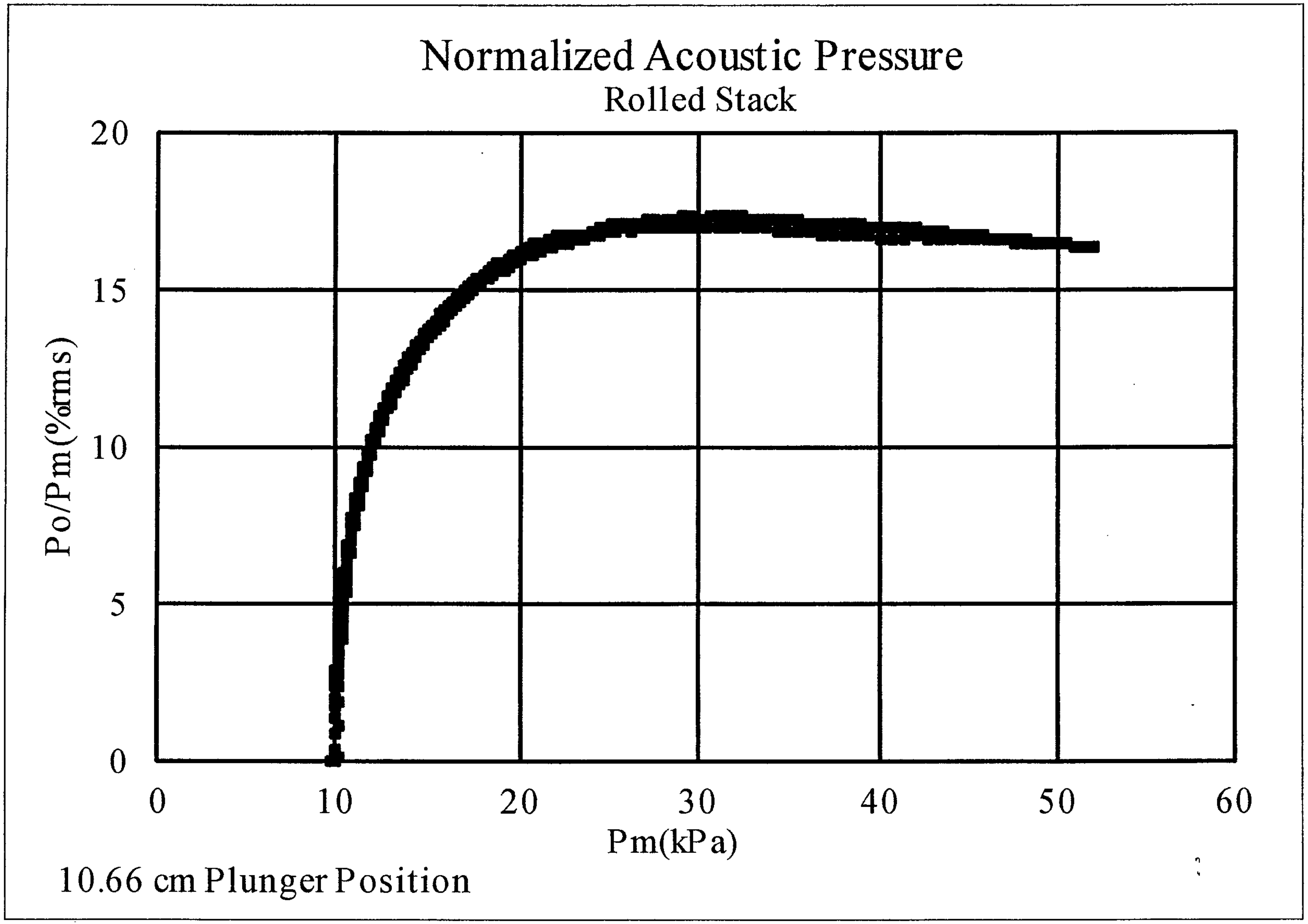


Figure 14. Rolled Stack 10.66 cm Normalized Acoustic Pressure.

Figure 15 shows the heat exchanger temperature differences for the same run. It can be seen that temperature oscillations were eliminated. With these more stable heater power values an efficiency plot could be developed directly from the data without averaging the powers over a stable mean pressure region.

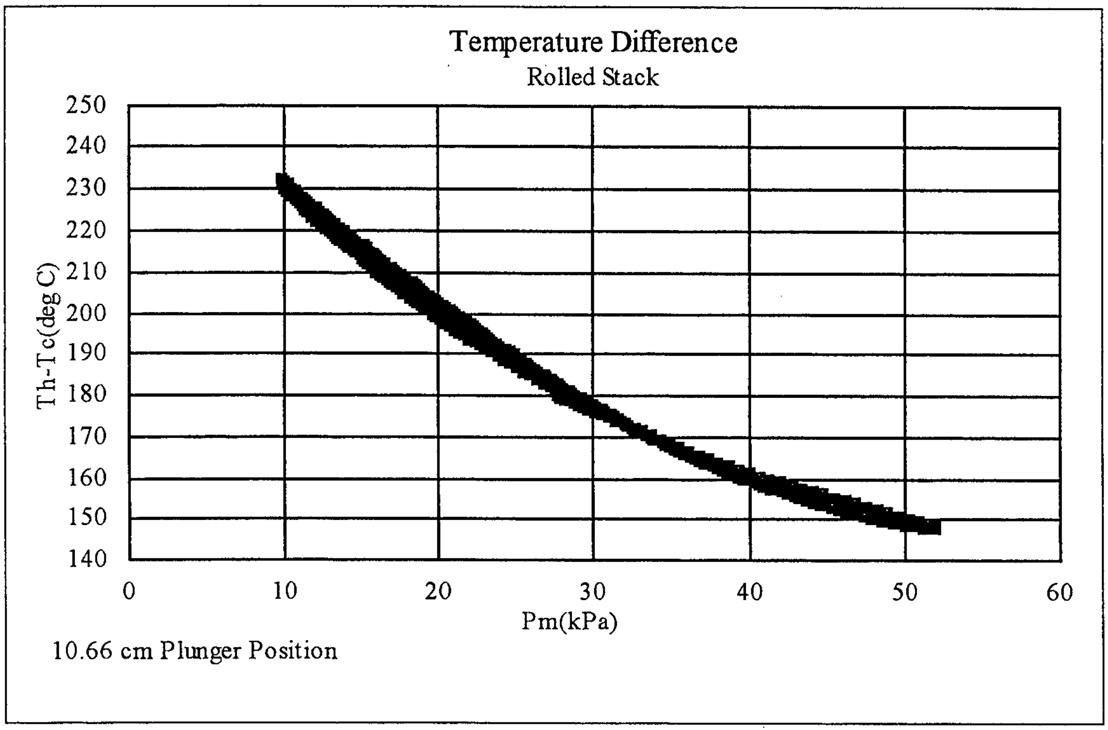


Figure 15. Rolled Stack 10.66 cm Temperature Difference.

The efficiency is defined as the acoustic work flux produced by the stack divided by the heat flux in. The acoustic work is a function of the square of the acoustic pressure amplitude. In terms of directly measured quantities a quasi efficiency equal to P_o^2/Q' was calculated. Q' is the heater power minus the heat leak below onset. This quasi efficiency will be adequate to compare the efficiencies of the two stacks at equivalent plunger positions, mean pressures and temperatures. A plot of the quasi efficiency is shown in Figure 16 for the rolled stack at the 10.66 cm plunger position. The vertical axis has units of $(kPa)^2$ /W. The heat leak below onset was 15.0 watts for this data set.

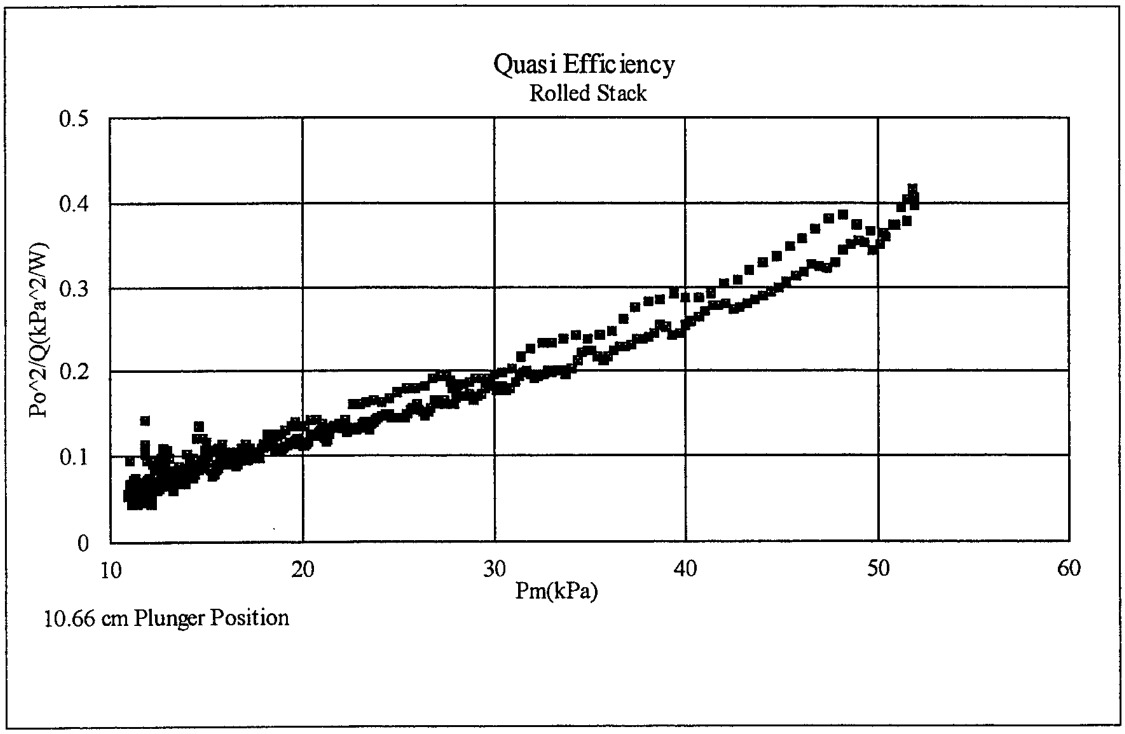


Figure 16. Rolled Stack 10.66 cm Quasi Efficiency.

After the data was obtained for the rolled stack the pin stack was installed in the prime mover and the experiment was repeated for the two plunger positions. The first measurements taken for the pin stack were at the 10.66 cm plunger position. The plot of normalized acoustic pressure versus mean pressure can be found in Figure 17. Figure 18 is a plot of the temperature difference between the hot and cold heat exchanger temperatures. The quasi efficiency as defined above is shown in Figure 19. A heat leak below onset of 35 watts was subtracted from the heater power in the efficiency calculation.

The experiment was repeated one last time for the pin stack at the 8.13 cm plunger position. Figure 20 shows the normalized acoustic pressure from the data obtained in the experiment.

The temperature difference between the hot and cold heat exchangers from the pin stack at the 8.13 cm plunger position is shown in Figure 21. In Figure 22 the quasi efficiency is plotted. A heat leak below onset of 58 watts was subtracted from the heater power prior to making these efficiency calculations.

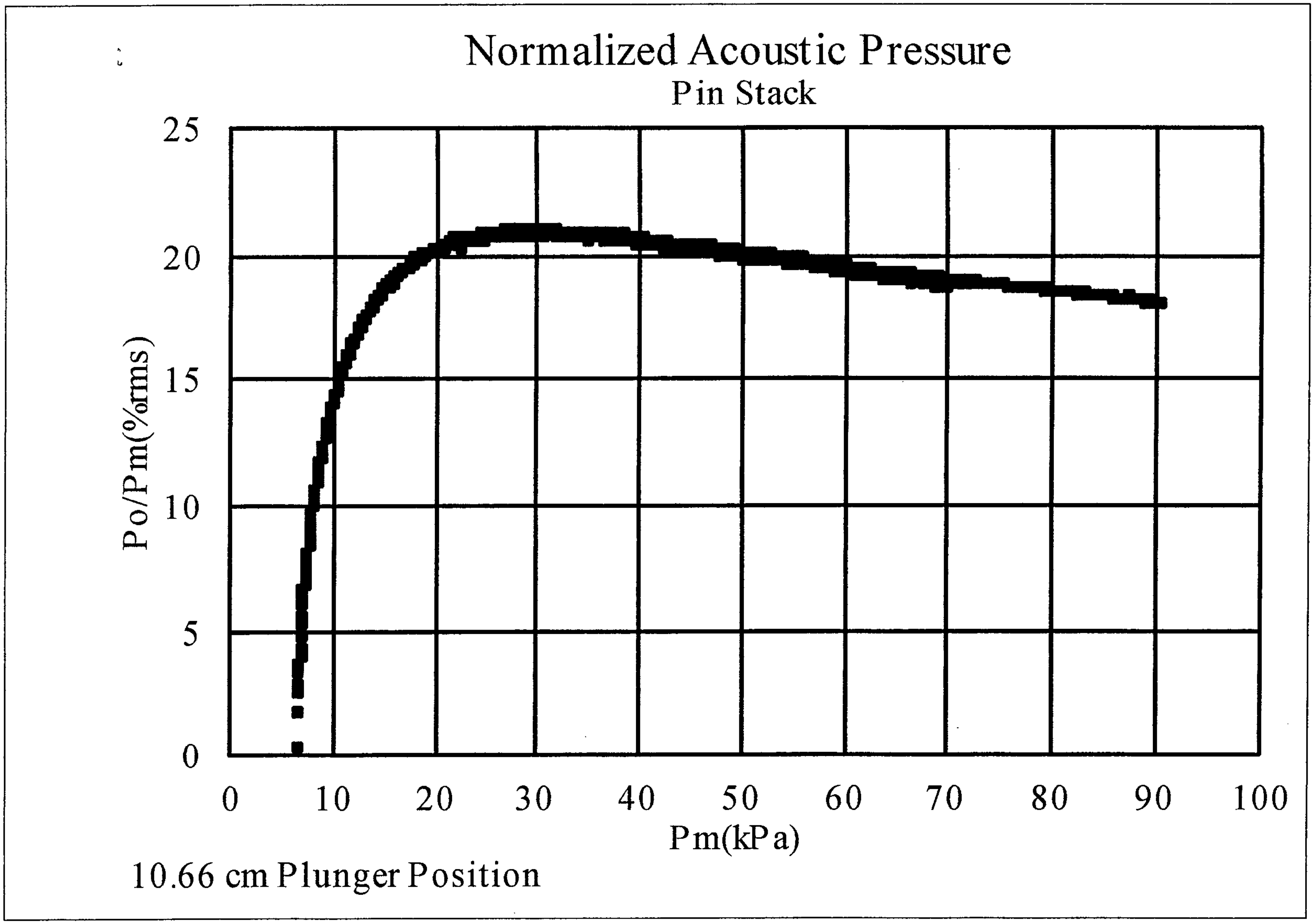


Figure 17. Pin Stack 10.66 cm Normalized Acoustic Pressure.

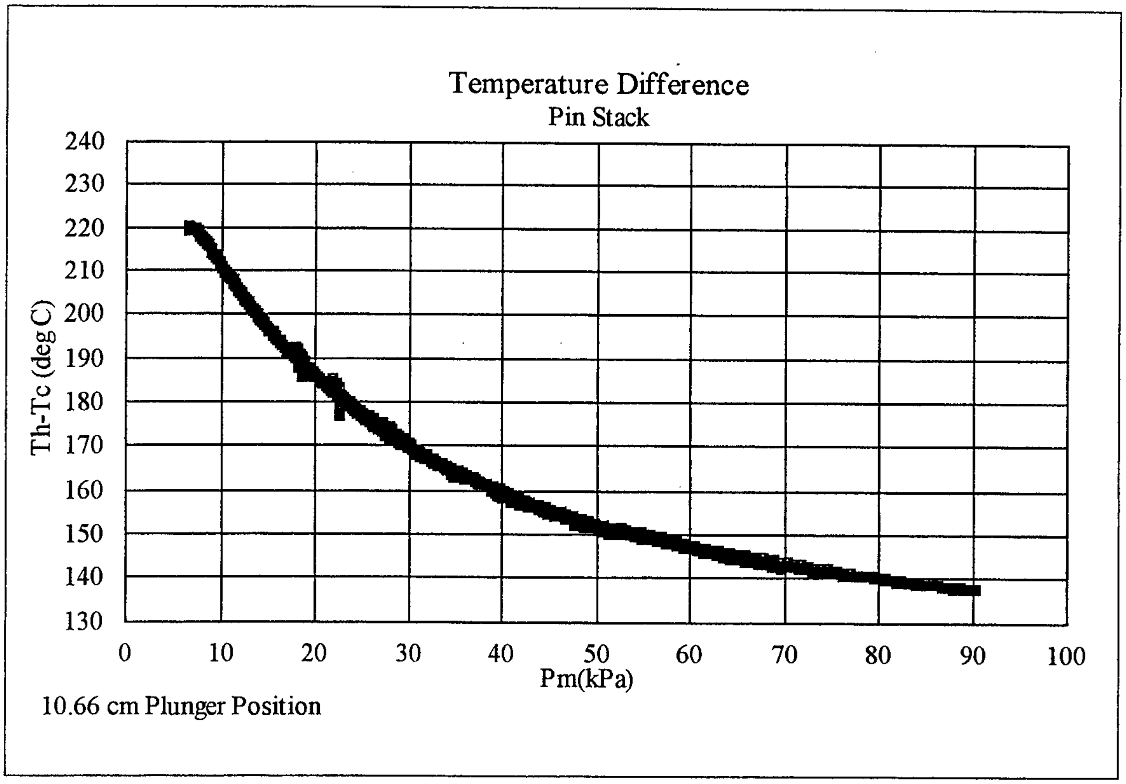


Figure 18. Pin Stack 10.66 cm Temperature Difference.

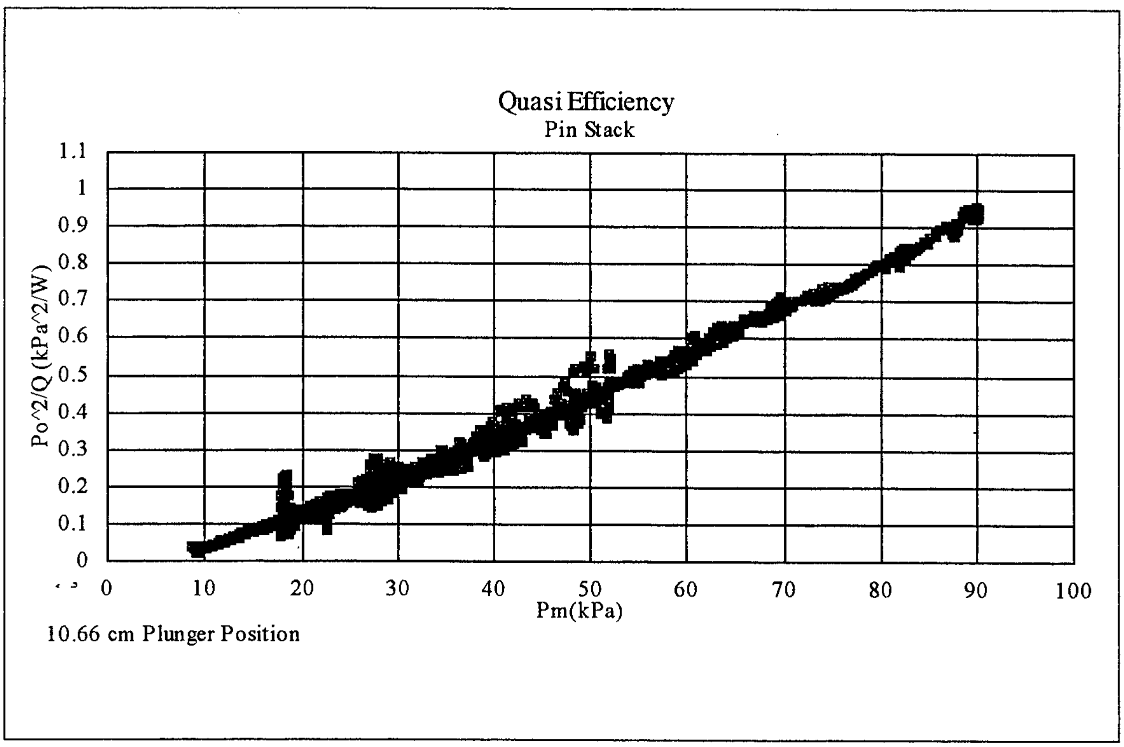


Figure 19. Pin Stack 10.66 cm Quasi Efficiency.

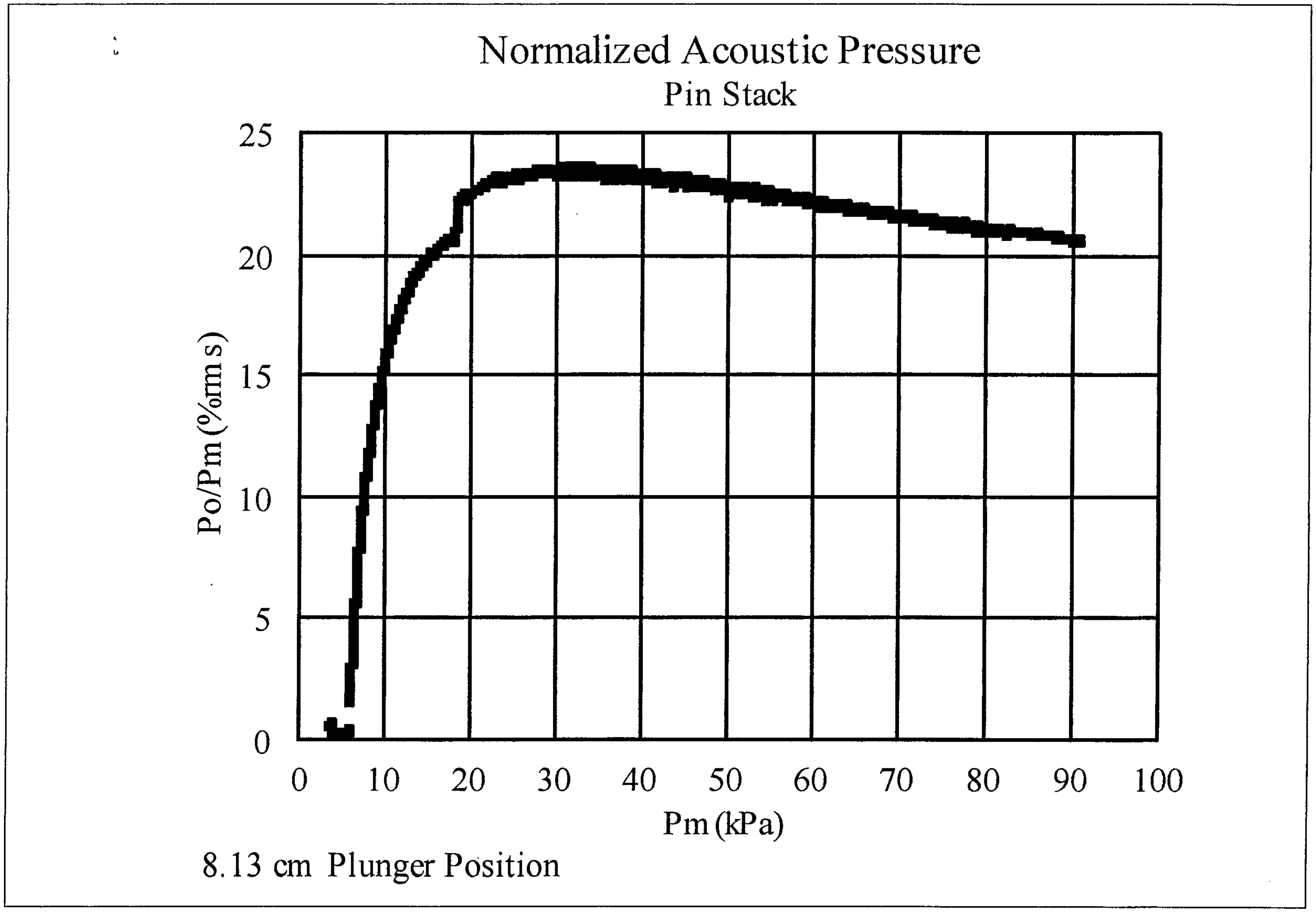


Figure 20. Pin Stack 8.13 cm Normalized Acoustic Pressure.

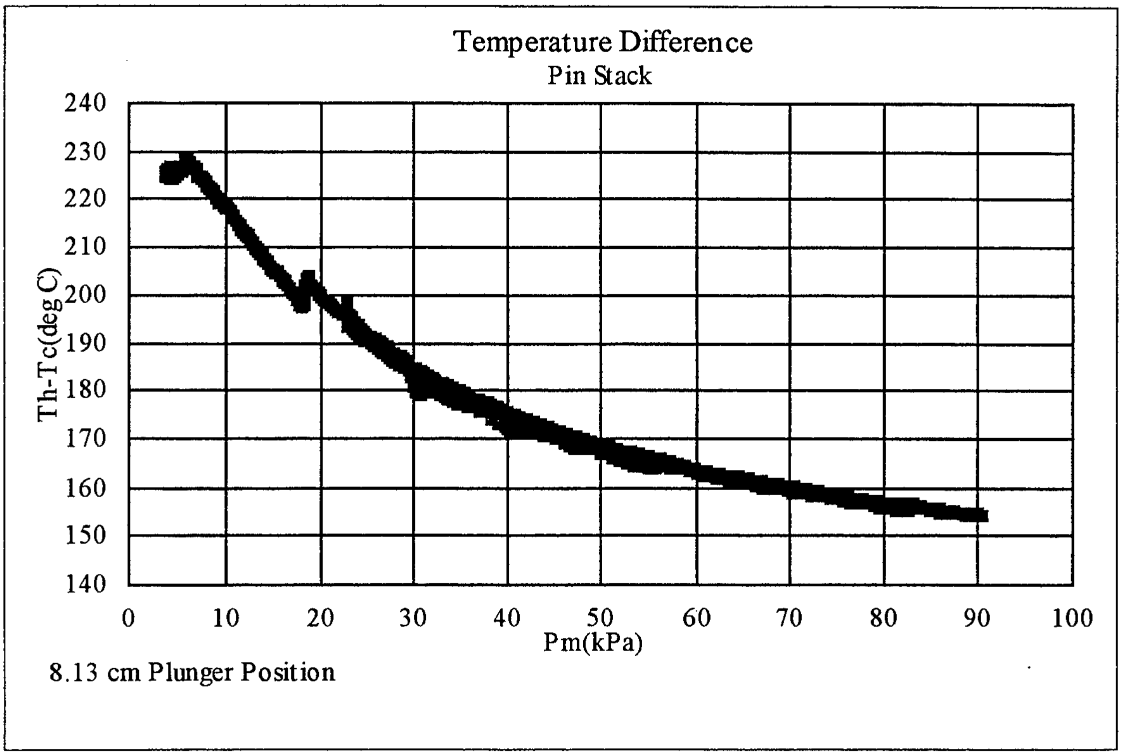


Figure 21. Pin Stack 8.13 cm Temperature Difference.

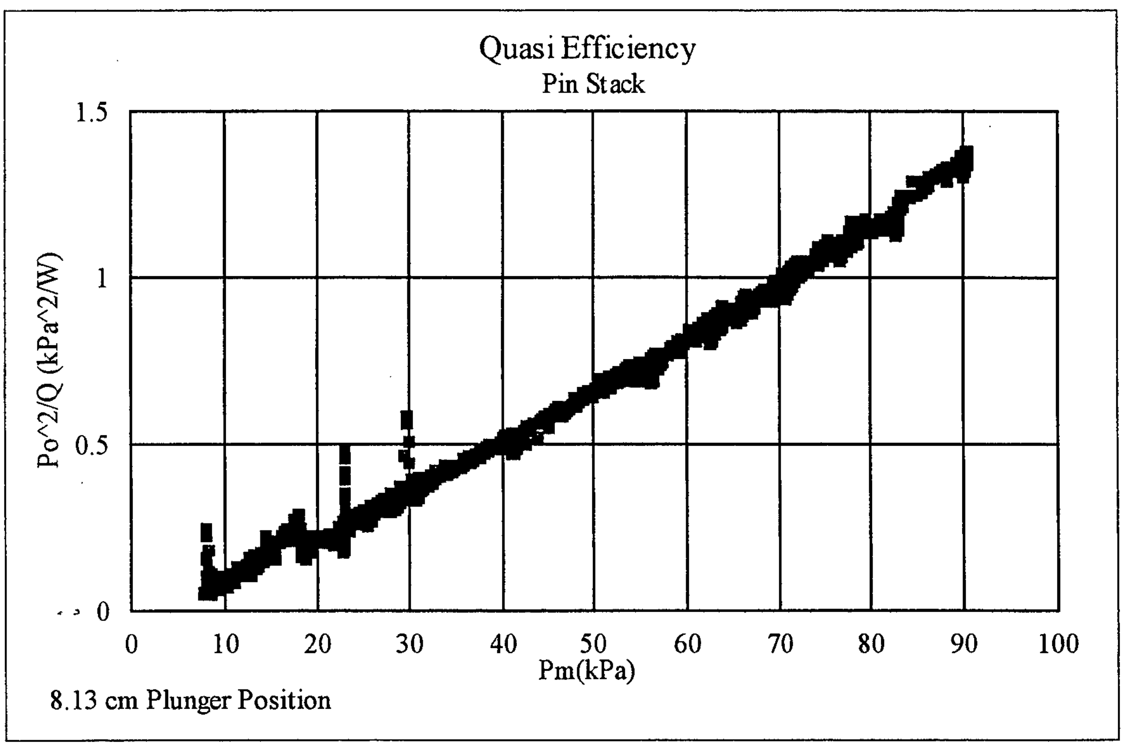


Figure 22. Pin Stack 8.13 cm Quasi Efficiency.

A sample plot of the power spectrum of the microphone output above onset is shown in figure 23. This was performed for the pin stack at the 8.13 cm plunger position. The mean pressure was 68.9 kPa during this measurement. It can be seen that decibel level of the second harmonic is 22 dB lower than the first harmonic which shows that most of the acoustic power is contained in the first harmonic. Also the waveform observed on the oscilloscope showed very little distortion even at these high acoustic pressure amplitudes (Po=15kPa). Appendix B shows four waveforms that were recorded for the pin stack at the 10.66 cm plunger position.

Since the 8.13 cm plunger position matched that used by Nessler in his thesis (1994), the acoustic pressures from the data could be compared to DeltaE predictions. Figure 24 is a comparison of the normalized acoustic pressures for both stacks at the 8.13 cm plunger position. The DeltaE predictions are about 6% below the measured values for the pin stack and about 15% below the measured values for the rolled stack. At P_m=50kPa the measured normalized acoustic pressure for the pin stack is 22.4% and 19.2% for the rolled stack, which is an increase of 16%.

It should be noted that Nessler set up his model for a mean pressure of 27.6 kPa, which is where the data best fits the DeltaE predictions. It can be seen that there is good agreement between the experimental results and the computer predictions over most of the range of mean pressures. However, since Nessler used a constant T_h-T_c of 190K and the actual T_h -T_c was considerably greater than this near onset, the experimental onset pressures are substantially below the DeltaE results. The prime mover used in the experiment was not designed to operate at mean pressures greater than atmospheric, so the DeltaE results above 100 kPa from Nessler's thesis could not checked.

Figure 25 shows a comparison of the experimental normalized acoustic pressures for the pin stack and the rolled stack at the 10.66 cm plunger position. No DeltaE data was available data for this plunger position. At a mean pressure of 50 kPa the pin stack's normalized acoustic pressure is 19.9% and the rolled stack's is 16.5%. The pin stack's normalized acoustic pressure is 21% greater than the rolled stack's at P_m=50 kPa.

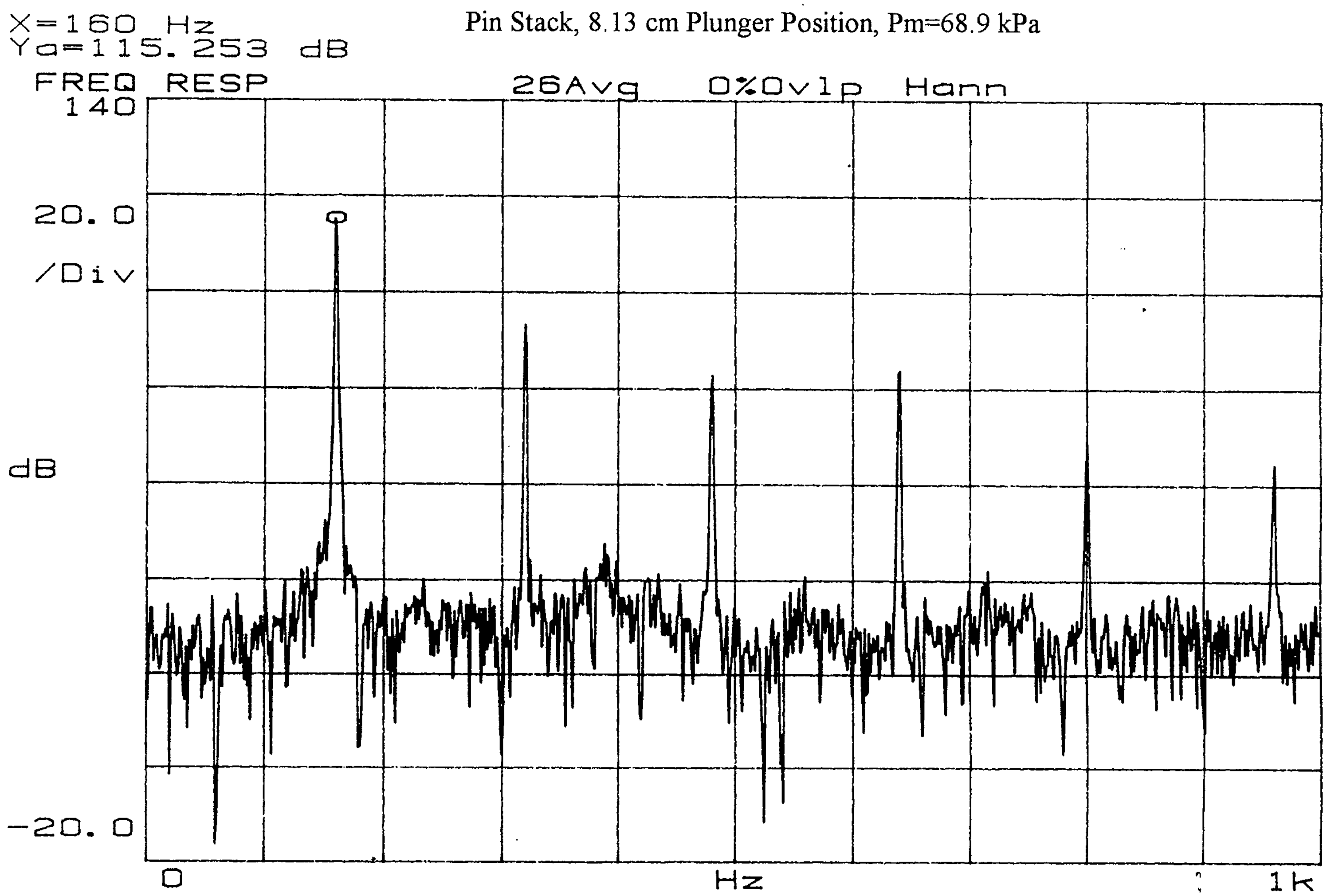


Figure 23. Pin Stack 8.13 cm Power Spectrum.

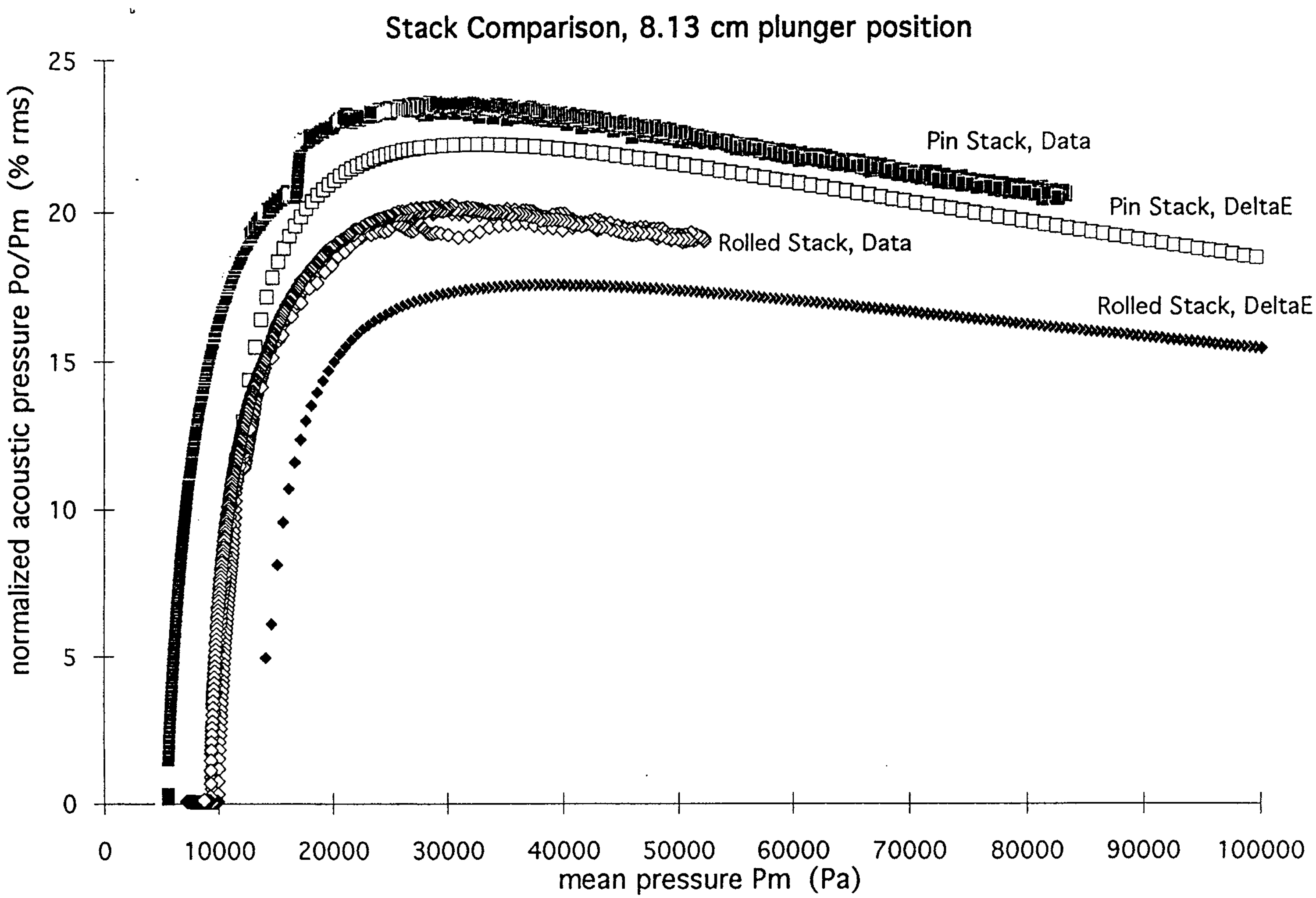


Figure 24. 8.13 cm Normalized Acoustic Pressure Comparison.

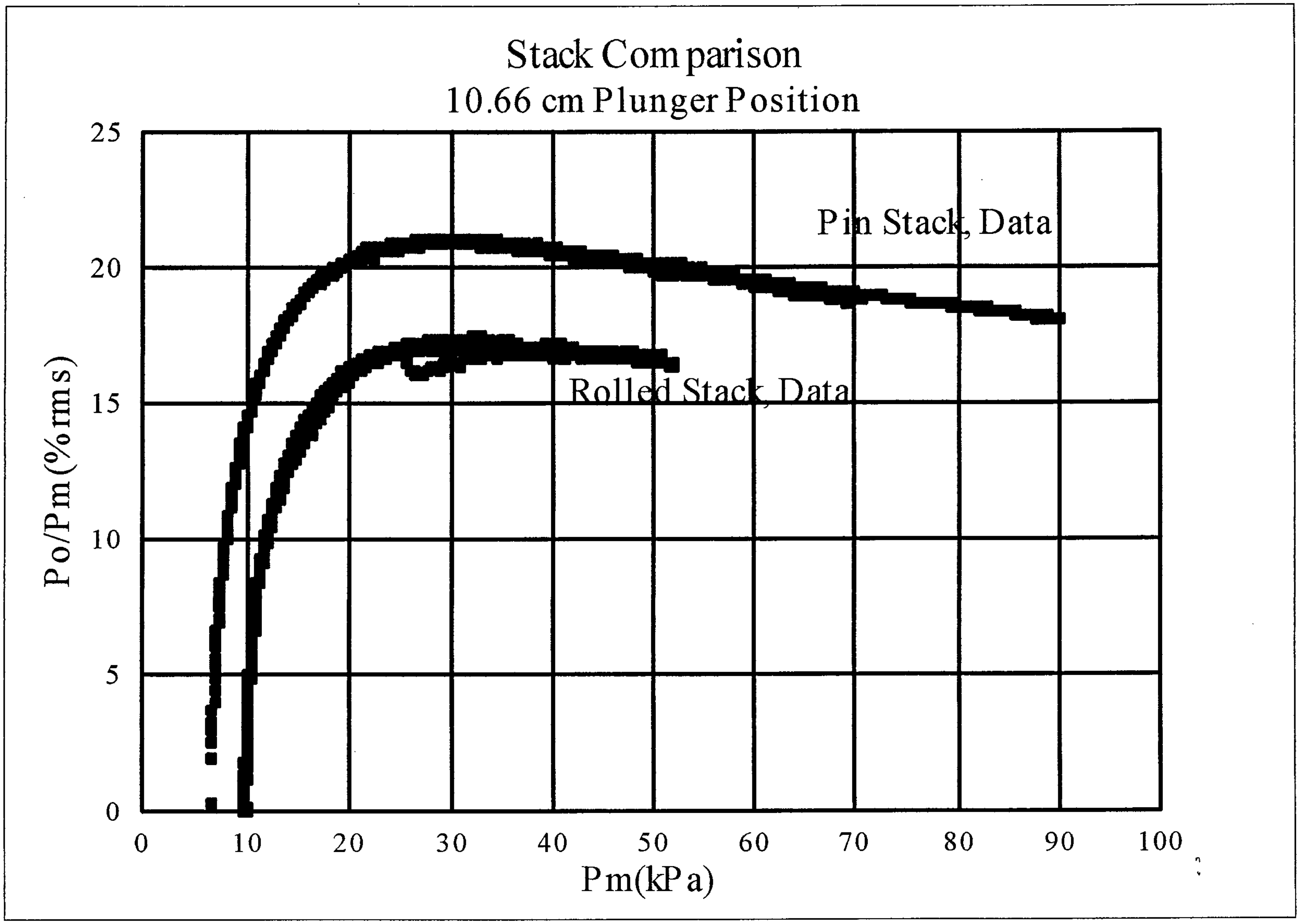


Figure 25. 10.66 cm Normalized Acoustic Pressure Comparison.

The next step in comparing the results from the pin stack to the rolled stack was to carefully sort through the data to find mean pressure values that were stable. The steady state values of the acoustic pressure and heater power were then extracted from the data sets for comparison. To compare the efficiency of the pin stack to the rolled stack the rms acoustic pressure squared was divided by the heater power minus the heat leak. This required careful scrutiny of the data to ensure that accurate heater power values were obtained. Figure 26 shows the results of the efficiency comparison for the 8.13 cm plunger position. It can be seen that only five points were found in the rolled stack data where the heater power could be confidently determined. The points were at the mean pressures where the experiment was stabilized for several minutes. This enabled the heater powers during that period of constant mean pressure to be averaged.

A final efficiency comparison can be seen in Figure 27. This plot is for both stacks at the 10.66 cm plunger position. At a mean pressure of 51 kPa the quasi efficiency of the pin stack is 0.47 and for the rolled stack it is 0.36. The pin stack's efficiency is 31% greater at that mean pressure. Again the difference between pin stack's efficiency and the rolled stack's is less at lower mean pressures.

Below 20 kPa the efficiency of the rolled stack is slightly greater than the pin stack at the 10.66 cm plunger position. This could be explained by the pin stack being more sensitive than the rolled stack to variations in the penetration depths which depend on the mean pressure (Nessler, 1994). Another factor could be that the heat leak was greater than the 35 watts used for the pin stack at the 10.66 cm plunger position. Because the mean pressure could not be stabilized below onset there were not very many heater power data points to compare with. The 35 watt figure is probably lower than the actual value, since it appears to go up with increased liquid nitrogen boil off, so it provides a conservative level for the comparison.

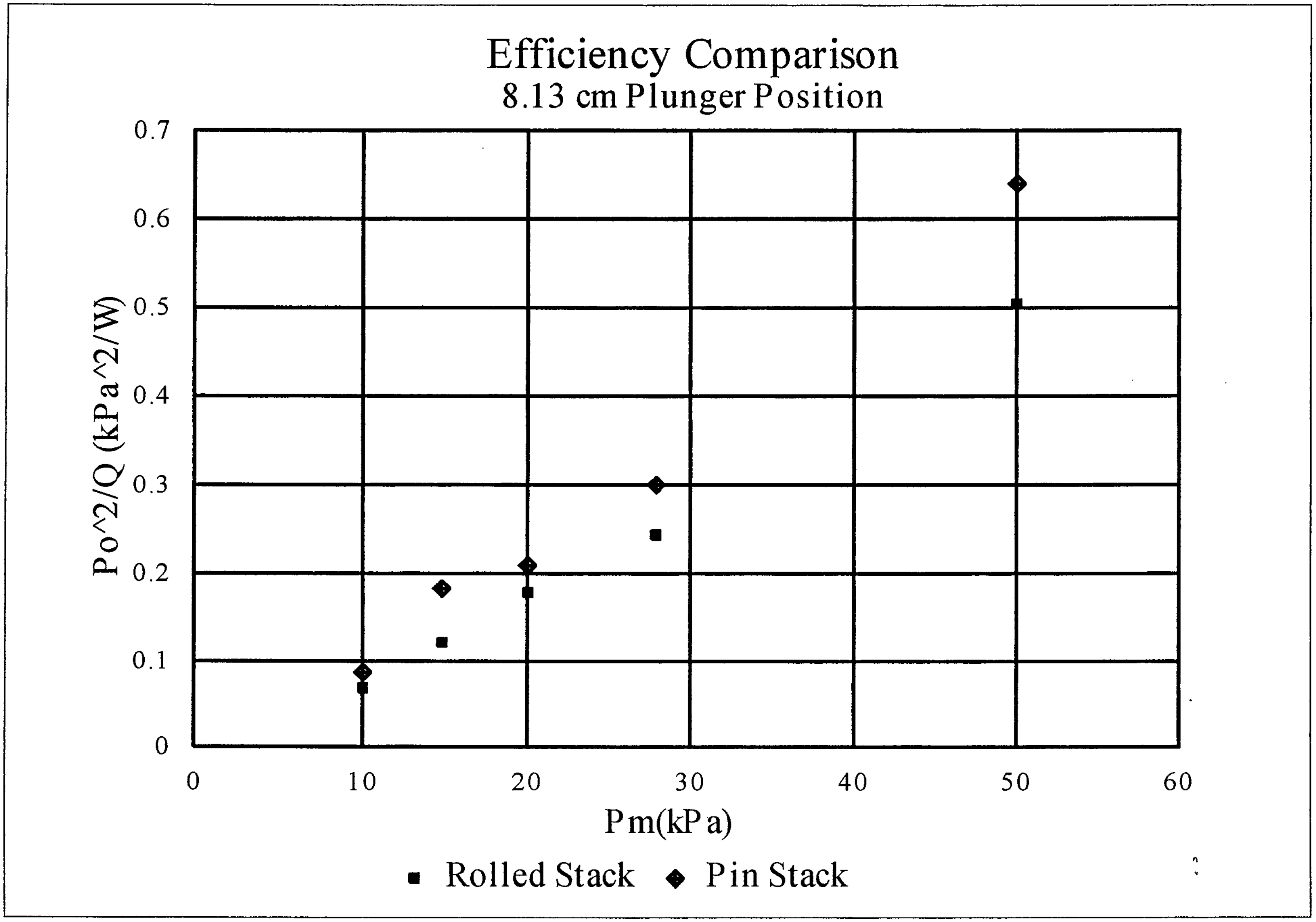


Figure 26. 8.13 cm Efficiency Comparison

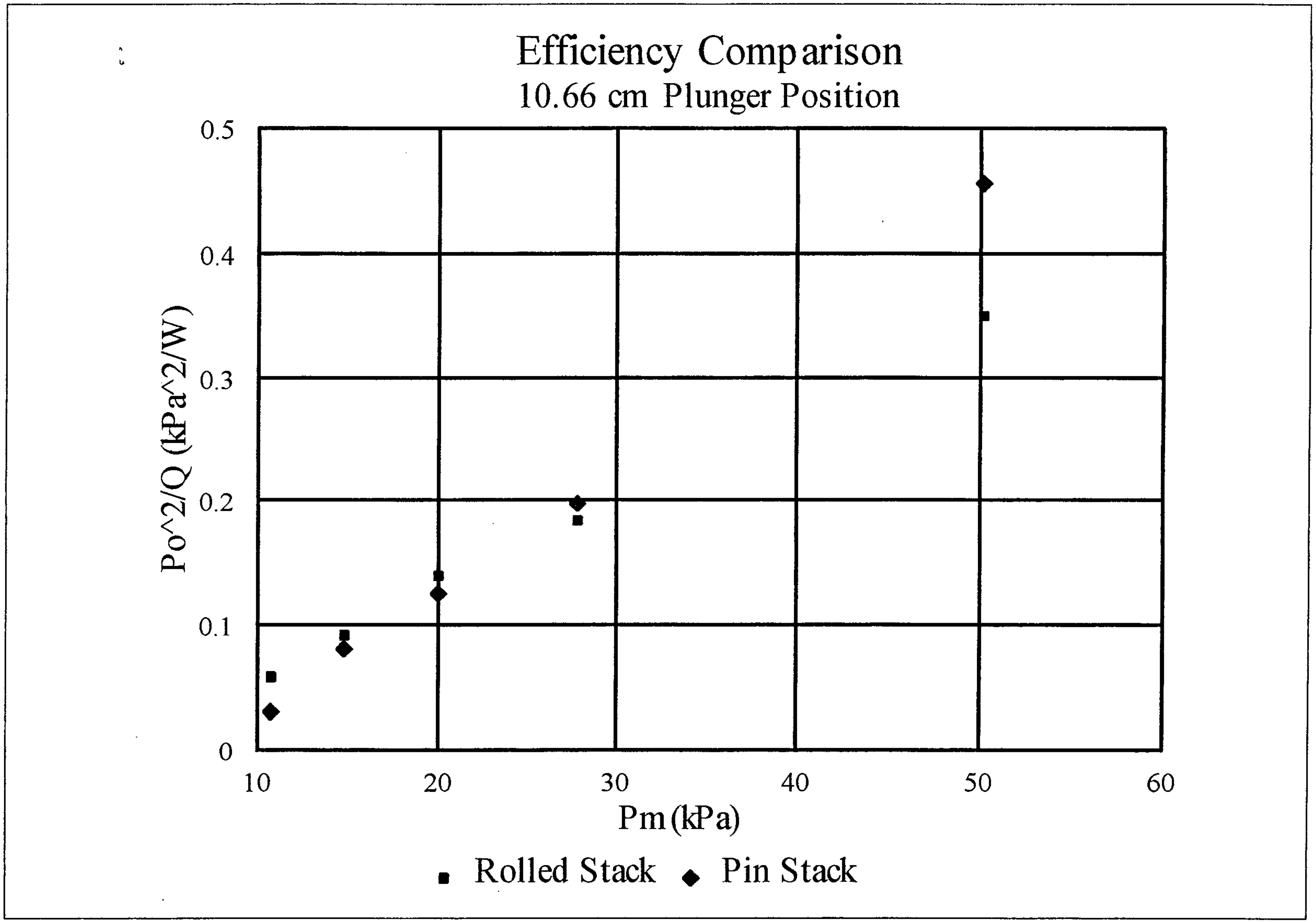


Figure 27. 10.66 cm Efficiency Comparison.

VI. CONCLUSIONS

Conducting the experiment for the same prime mover configurations has allowed the comparison of performance of a pin stack to a conventional rolled stack. The Q for the prime mover in air at atmospheric pressure is 24.6 for the rolled stack and 29.1 for the pin stack at the 8.13 cm plunger position. Since the Q can be expressed as 2π times the energy stored divided by the energy lost per acoustic cycle, the higher Q indicates that the pin stack has less losses due to dissipation. At the 10.66 cm plunger position the Q is 26.8 for the pin stack, which is lower than that at the 8.13 cm plunger position indicating that the losses are greater when the stack is further from the pressure antinode.

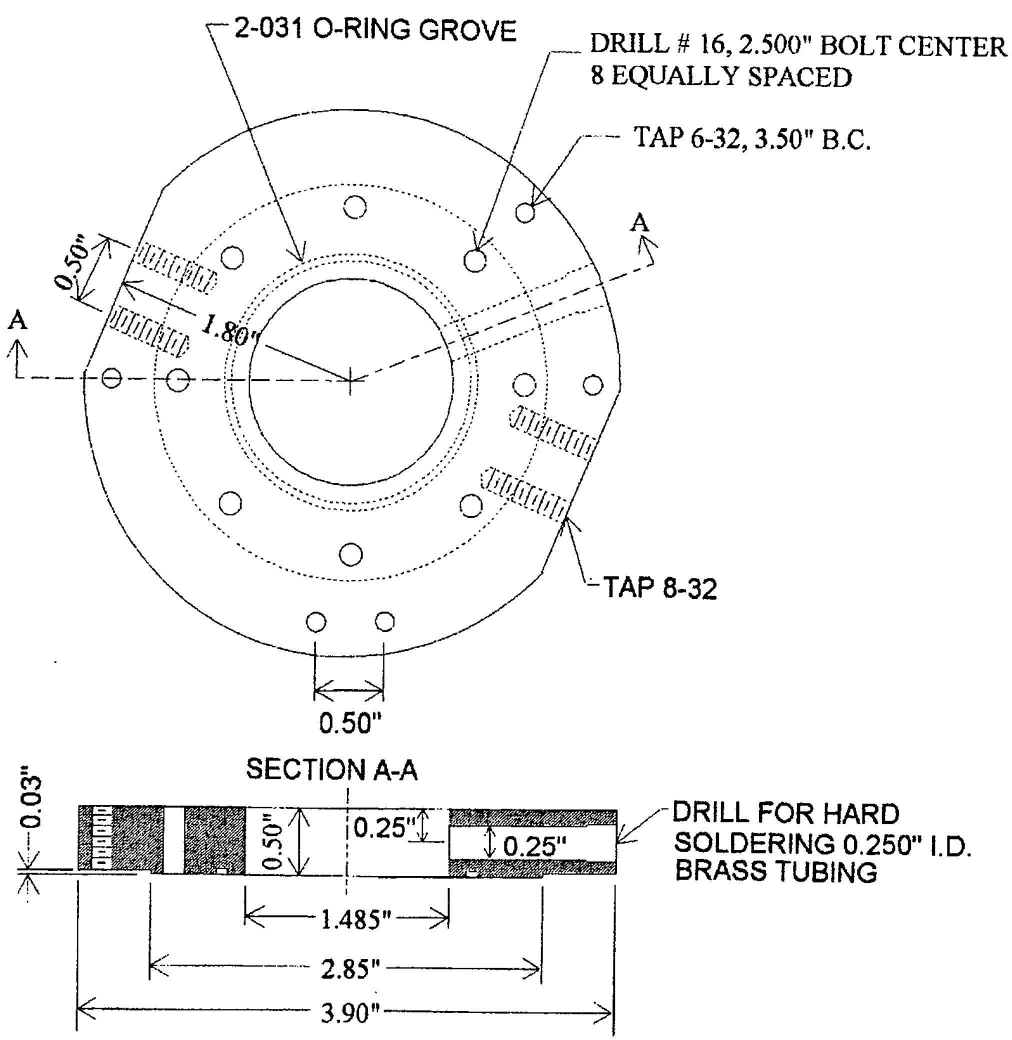
With the prime mover filled with neon at a mean pressure below onset, the Q was also higher for the pin stack than the rolled stack. At a mean pressure of 4.5 kPa the Q was 38.4 for the pin stack and 12.2 for the rolled stack at the 8.13 cm plunger position. The cold end of the prime mover was submerged in liquid nitrogen while the hot end was held at ambient temperatures for these measurements.

Onset, when the prime mover starts producing sound, occurs when 1/Q is equal to zero or the Q is infinite. Onset occurred at lower mean pressures for the pin stack than for the rolled stack. At the 8.13 cm plunger position the onset pressure was P_m=9.4 kPa for the rolled stack and 5.55 kPa for the pin stack. At the 10.66 cm plunger position onset occurred at P_m=10.1 kPa for the rolled stack and 6.57 kPa for the pin stack.

Above onset the pin stack produced rms acoustic pressures which were greater than those produced by the rolled stack. At the 10.66 cm plunger position and a mean pressure of 50 kPa the normalized rms acoustic pressure was 16.5% for the rolled stack and 19.9% for the pin stack, an increase of 21%. At the 8.13 cm plunger position and P_m=50 kPa the normalized acoustic pressures were 19.2% for the rolled stack and 22.4% for the pin stack, an increase of 16%. The acoustic pressures measured for the pin stack at the 8.13 cm plunger position agree with those predicted by DeltaE (Nessler,1994) to within 6%.

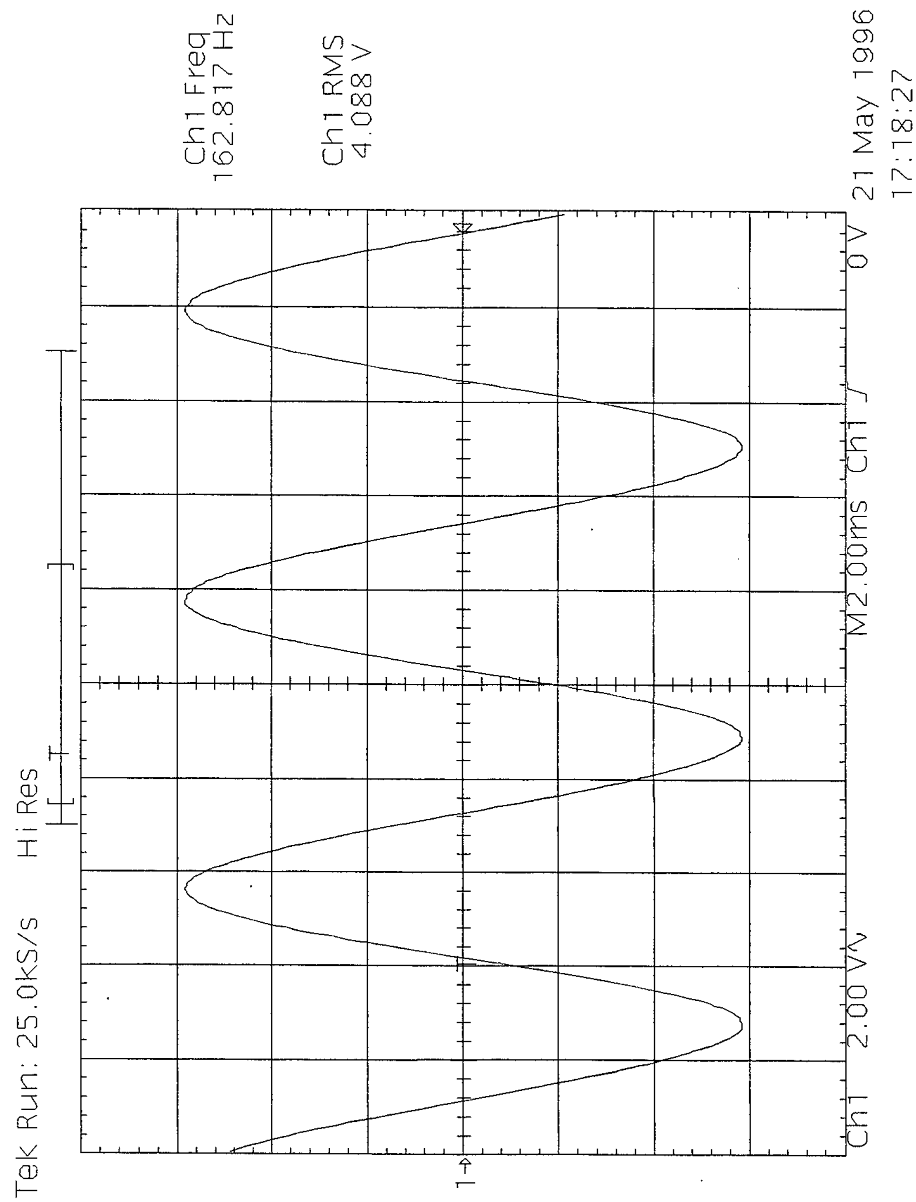
The efficiency of the prime mover is expressed as the acoustic power produced by the stack divided by the heater power put in. The acoustic power is a function of the acoustic pressure amplitude squared. Efficiency comparisons were made by dividing the rms acoustic pressure squared by the heater power measured. For the prime mover at a mean pressure of 50 kPa and the 8.13 cm plunger position the pin stack's efficiency divided by the rolled stack's was 1.25. This is an increase of 25%. For the 10.66 cm plunger position the ratio of the pin stack's efficiency to the rolled stack's is 1.3 or an increase of 31%.

APPENDIX A. THERMOCOUPLE FLANGE SPECIFICATIONS

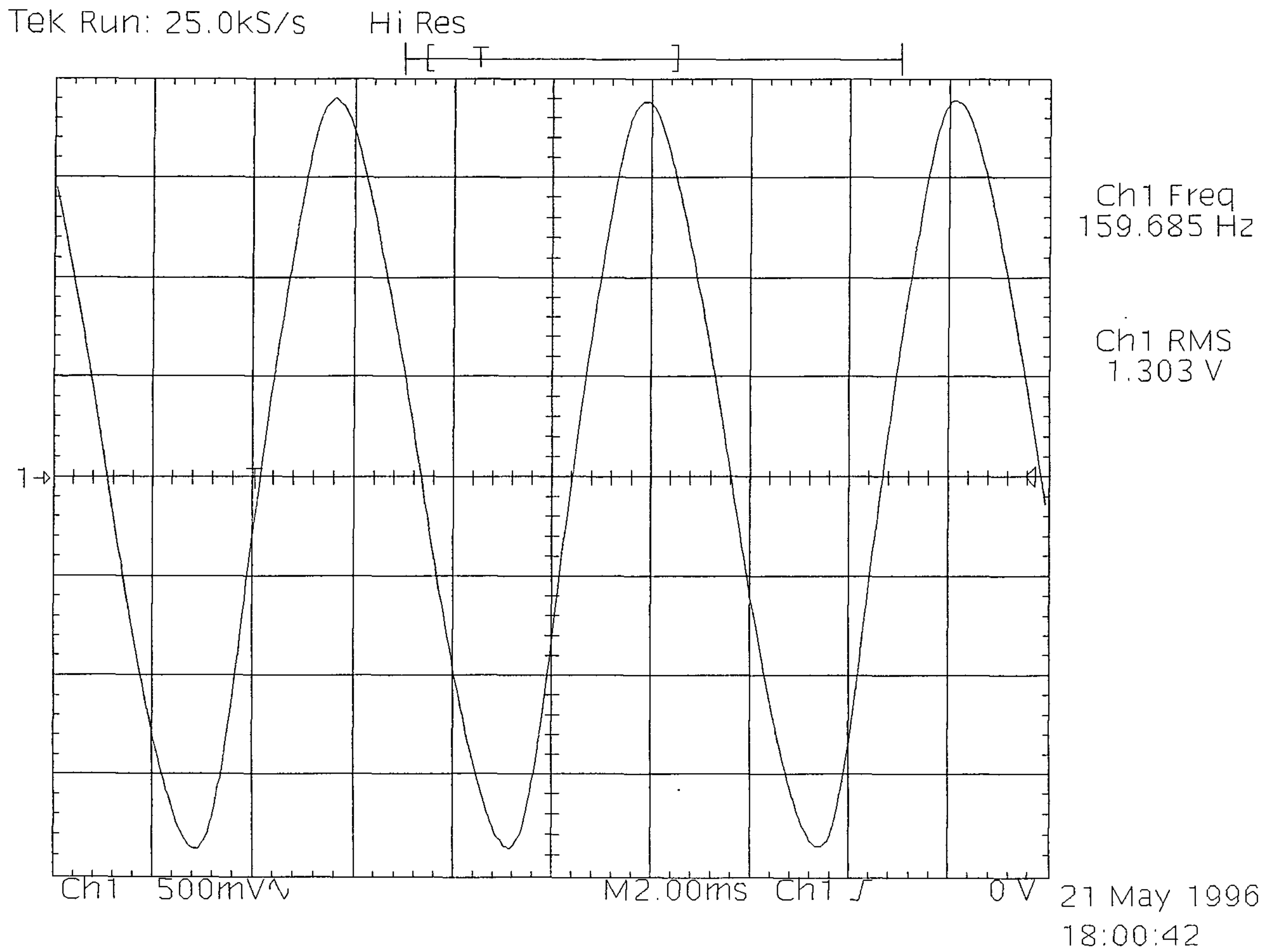


APPENDIX B. PIN STACK WAVEFORMS

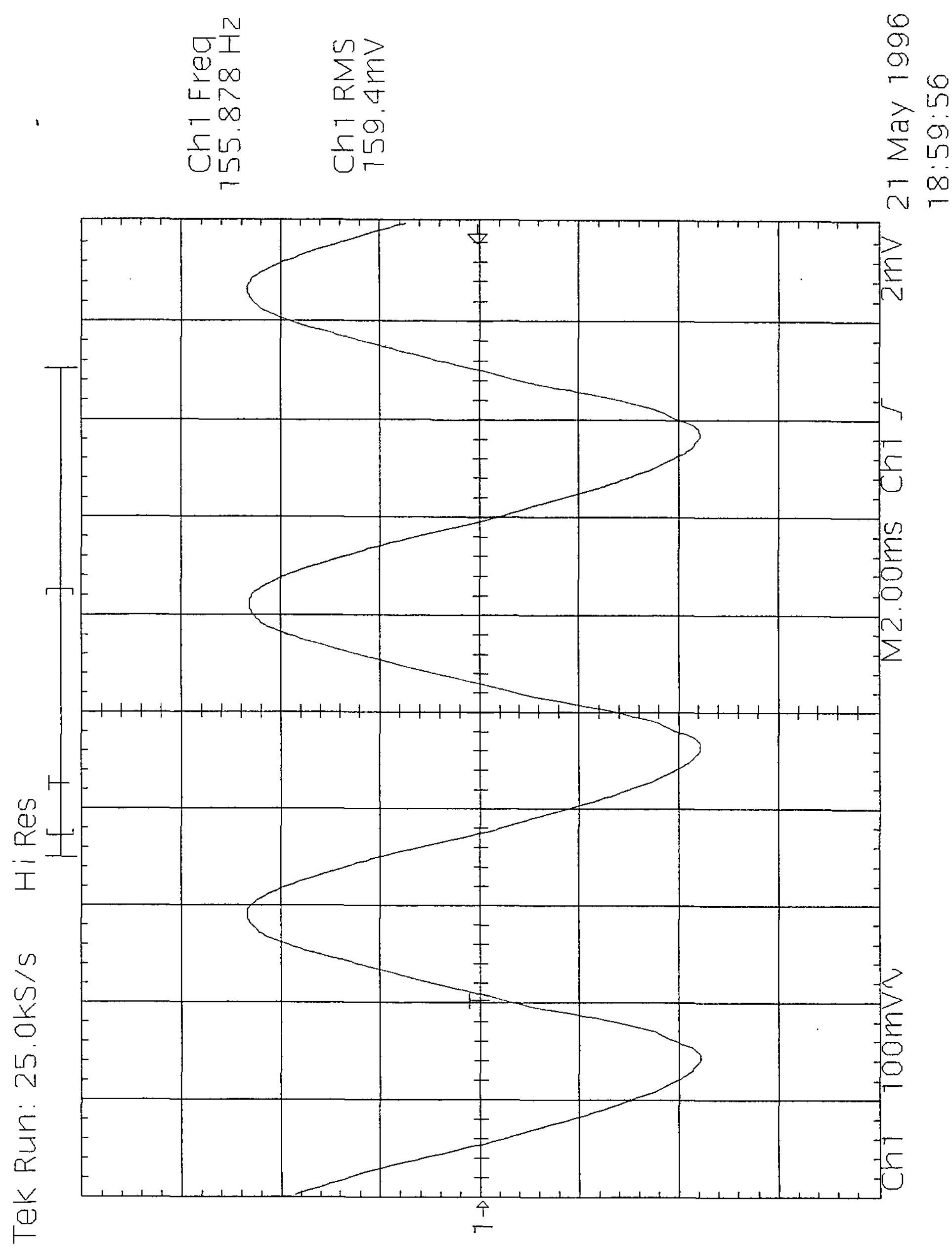
This appendix contains four waveforms recorded from the digital oscilloscope for pin stack at the 10.66 cm plunger position.



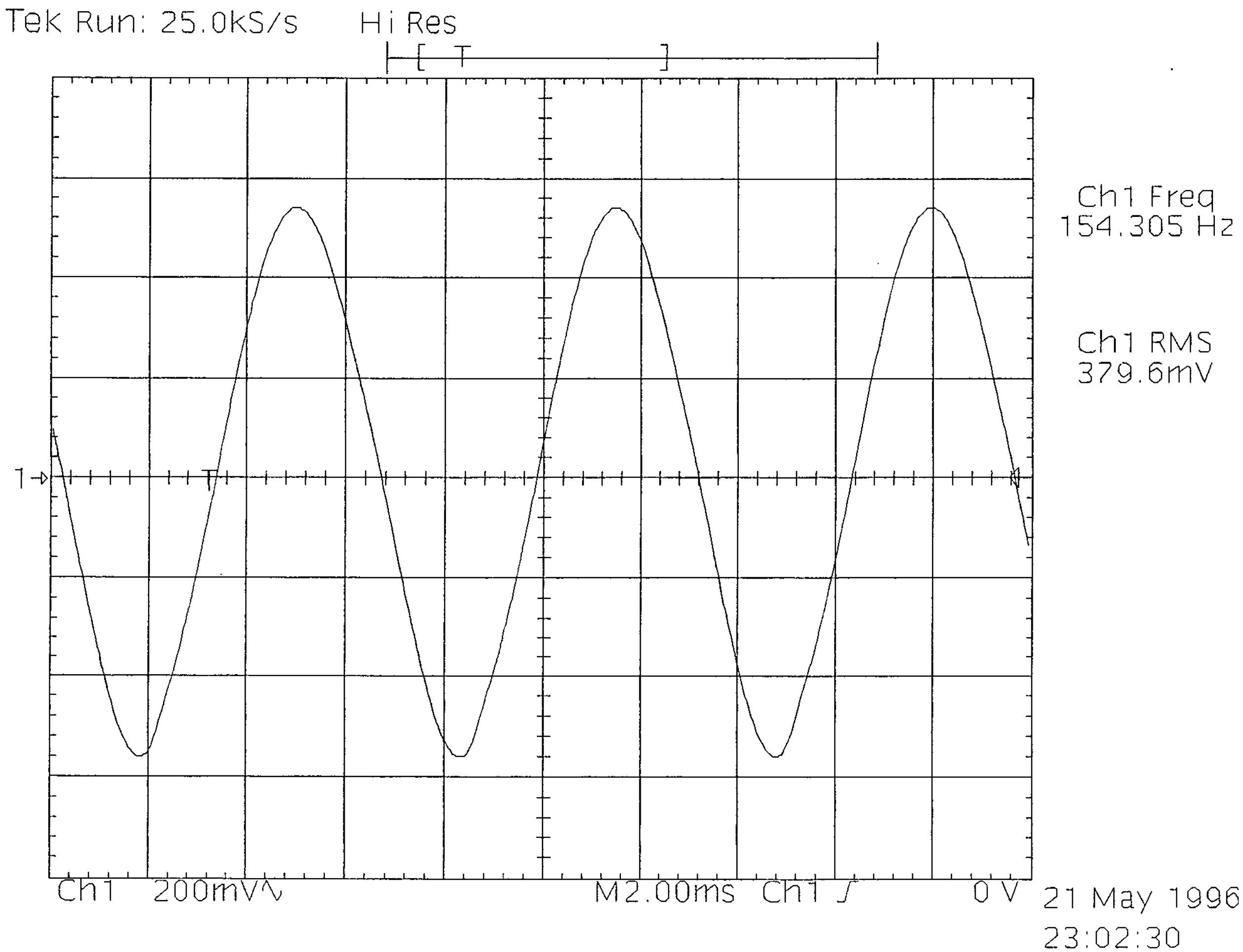
C-1. Pm=11.4 kPa, Po/Pm=15.6 % rms.



C-2. Pm=15.8 kPa, Po/Pm=19.0 % rms



C-3. Pm=39.3 kPa, Po/Pm=20.5 % rms.



C-4. Pm=88.9 kPa, Po/Pm=18.2 % rms.

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